TECHNICAL REPORT 2040
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Approved for public release.

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ADMINISTRATIVE INFORMATION

The work described in this report was prepared for the Environmental Security Technology Certification Program (ESTCP) under Project ER-0919 on "Demonstration of an In-Situ Friction-Sound Probe for Mapping Particle Size at Contaminated Sediment Sites."

Dr. D. Bart Chadwick, Space and Naval Warfare Systems Center Pacific (SSC Pacific), is the principal investigator of this project.

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SB

EXECUTIVE SUMMARY

OBJECTIVES OF DEMONSTRATION

The Navy, Department of Defense (DoD), and other government and private entities are in the process of identifying, assessing, and remediating numerous hazardous waste sites that are the result of decades of waste management practices that led to the release of contaminants to soil, sediment, and groundwater in coastal environments. At contaminated sediment sites, it is generally accepted that the affinities of contaminants for fine-grained sediment result in high contaminant concentrations in areas that are characterized by fine sediments. (Calvert, 1976; Warren, 1981). In contrast, at groundwater surface water interaction (GSI) sites, groundwater discharge of more mobile, dissolved-phase contaminants is often associated with coarser-grained, permeable sediment units (Fetter, 1994). Knowledge of grain size at sediment study sites can provide lines of evidence that can be applied to identify potential areas of contaminated sediment and contaminant discharge zones.

Field surveys for grain size can require a full sampling regime including substantial analytical costs. The sediment friction-sound probe (SED-FSP) technology was proposed to quickly acquire grain-size information at a lower cost. The overall objective of this project was to field demonstrate the effectiveness of the SED-FSP for direct in-situ measurement of grain size at contaminated sediment and groundwater–surface water interaction (GSI) sites. The objective was accomplished through the following activities:

- Development of a commercial prototype friction-sound probe
- Verification of sensor performance in the laboratory
- Field demonstration and validation at varying application regimes to delineate areas of potential contamination and groundwater discharge zones

Three types of sites were selected to field demonstrate the technology: (1) a GSI site, (2) a contaminated sediment site, and (3) a contaminated sediment, thin-layer containment cap where the vertical profiling capabilities of the technology were demonstrated.

TECHNOLOGY DESCRIPTION

The friction-sound intensity at a particle/sensor interface is a linear function of the radius of particles in contact with the sensor surface and the velocity of the probe (Koomans, 2000). The SED-FSP technology employs this relationship to infer grain size by measuring the acoustic response as a probe with an imbedded microphone that penetrates a sediment matrix. The microphone signal is processed through an on-board electronics interface package and transmitted to recording software. A pneumatic drive unit mounted on an aluminum frame assembly drives the probe into the sediment bed at a controlled speed. Grain size is determined by comparing the acoustic response to responses of prepared sediments of known grain sizes; the calibrations are performed prior to the field deployment.

The unit was demonstrated at three application regimes: (1) a contaminated sediment site, (2) a GSI site, and (3) a contaminated sediment sand cap. Site surveys of the areas were conducted with the SED-FSP system and responses were used to generate grain-size maps. For two of the areas, the system was used to generate grain-size depth profiles. Validation of the technology was accomplished by comparing SED-FSP response to laboratory-validated measurements of site sediments and through comparison to previously conducted site surveys.

DEMONSTRATION RESULTS

The SED-FSP technology was demonstrated at three locations: (1) Naval Base San Diego at the mouth of Chollas Creek in San Diego Bay, (2) Naval Air Station North Island (NASNI) Installation Restoration (IR) Site 9, and (3) the Active Capping Pilot Study Site on the Anacostia River in Washington, D.C. At Chollas Creek, 20 stations were acquired, including a collection of validation samples at all stations. The resulting survey showed that the largest grain sizes measuring in the medium sand range were acquired at the mouth of the creek trending to finer sediments into San Diego Bay and upstream into Chollas Creek. These results were supported by an earlier site assessment performed in 2004 by SSC Pacific investigators that found the same trends.

Two surveys were performed at the NASNI IR Site 9 location. During the first field effort the SED-FSP was deployed at 27 locations for collection of validation samples. The SED-FSP succeeded in determining size classifications for the validation sediments to greater than 85% accuracy in all instances where the response was invalidated by the SED-FSP under predicted grain size. During the second deployment at NASNI, the SED-FSP was used to survey the entire study area, which included 12 transects, 9 to 12 stations per transect. The results were used to generate grain-size maps of four depth layers, which were used as evidence supporting previous assessments of contaminant transport at the site. The results were also used to support the sampling plan for a comprehensive assessment of IR Site 9 that is anticipated for the near future.

At the Active Capping Pilot Study Site on the Anacostia River, a sand cap installed in March 2004 was investigated. The purpose of the deployment was to demonstrate the capability of the SED-FSP to acquire grain-size measurements in subsurface sediments, to delineate the capping material/native sediment interface, and to provide information on the capping thickness. Of the 44 core sections submitted for validation, the SED-FSP correctly predicted 42 size classification results. The SED-FSP identified the subsurface capping material/sediment interface and confirmed that its thickness and boundaries have remained intact. This was confirmed with the sediment cores, which showed that the capping material remained intact with little dispersion beyond the cap boundaries or into the underlying native sediment.

IMPLEMENTATION ISSUES

The costs associated with implementing the technology are similar to costs associated with sediment sampling deployments. The key cost drivers are labor, transportation/shipping, field deployment costs, and capital equipment costs. The capital costs for the technology could be recovered quickly, as they are low. The demonstrations were performed at full scale, therefore scale-up is a non-issue. Costs related to sample analysis relate to data reduction by the user by spreadsheet or other processing software; costs are not incurred for sample analysis as the SED-FSP performs this function in real time.

Prior to each of the field demonstrations, the SED-FSP was calibrated using prepared sediments of known grain sizes. When employed in the field, the system tended to under-predict grain size based on analysis of validation samples. Recalibration of the system using a limited number of site sediments as calibration samples resulted in the unit performing within the performance metrics. Therefore, site-specific calibrations are required using site sediments. Field testing of the unit confirmed applicability of the technology where fine sediments were differentiated from sandy sediment and between sub-classifications of sands, sediments in the clay range (< 3.9 μm) were not acquired either as a SED-FSP response or as results of laboratory analysis of site samples. Laboratory testing also showed that the SED-FSP did not resolve or accurately predict sizes of this range and smaller. The unit should therefore be considered for use where differentiation of sands and fines are required. Differentiation of silt (3.9 to 63 μm) and clay sizes was not validated.

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1. INTRODUCTION

1.1 BACKGROUND

The Navy, Department of Defense (DoD), and other government and private entities are in the process of identifying, assessing, and remediating a large number of hazardous waste sites that are the result of decades of waste management practices, resulting in the release of contaminants to soil, sediment, and groundwater in coastal environments. Areas of potential concern at these sites are identified by conducting chemical, toxicological, as well as geophysical (including grain size analysis) surveys during the characterization phase of the site assessment. At contaminated sediment sites, it is generally accepted that the affinities of contaminants for fine-grained sediment result in high contaminant concentrations in areas that are characterized by fine sediments. (Calvert, 1976; Warren, 1981; Förstner, 1989; Santschi, Lenhart, and Honeyman, 1997). In contrast, at groundwater–surface water interaction (GSI) sites, groundwater discharge of more mobile, dissolved-phase contaminants is often associated with coarser-grained, permeable sediment units (Fetter, 1994). In combination with other groundwater tracers (e.g., temperature and salinity; Chadwick and Hawkins, 2008), grain size can provide an important line of evidence for identifying potential discharge zones. However, at most contaminated sediment sites, grain size analysis is typically carried out only as part of the overall suite of physical, chemical, and toxicological analyses during the characterization stage of a Remedial Investigation/Feasibility Study (RI/FS).

Determination of sediment grain size is normally based on core or grab samples collected in the field and analyzed in the laboratory. Field collection of these samples can be expensive, requiring boats and crews, load-handling equipment, sampling crew and gear, sample handling, and storage and custodial management. The traditional analytical method for measuring grain size is a time- and labor-intensive process. Sand, gravel, and larger particles are separated with sieves; silts and clays are determined by sedimentation according to the Stokes Law through pipettes (Plumb, 1981) or hydrometer (ASTM, 1988). Various optical techniques, electro-resistance (Coulter Counter) and laser diffraction methods are available for measurement of particle size distributions in the laboratory after collection of sediment samples. While sediment systems have inherently large spatial variability and generally require relatively dense sampling, sampling density by traditional methods is generally limited because the analyses are labor intensive and costly. The turnaround time between sample collection and results can also be excessive, especially in the context of adaptive sampling strategies such as the Triad approach promulgated by the U.S. Environmental Protection Agency (USEPA) for decision-making for clean-up of waste sites (Crumbling, 2004). From the perspective of accurate, fast, adaptive assessments, new technologies are required. A rapid in-situ, cost-effective screening method is needed for grain size characterization at contaminated sediment and GSI sites to reduce time and cost and to promote adaptive assessment and management strategies.

1.2 OBJECTIVES OF THE DEMONSTRATION

The overall objective of this project was to field demonstrate the effectiveness of a sediment friction-sound probe (SED-FSP) for direct, in-situ measurement of grain size at contaminated sediment and GSI sites.

The objective was accomplished through the following:

- Development of a commercial prototype friction-sound probe
- Verification of sensor performance in the laboratory
- Field demonstration and validation at three application regimes to delineate areas of potential contamination and groundwater discharge zones

Three types of sites were selected to field demonstrate the technology: (1) a contaminated sediment site, (2) a GSI site, and (3) a contaminated sediment thin-layer containment cap. The demonstration sites provided a broad range of sediment grain size conditions ranging from predominantly sandy to predominantly fine and a site where delineation of subsurface sediments could be evaluated.

The mouth of Chollas Creek at Naval Station San Diego in San Diego Bay is a Total Maximum Daily Loads (TMDL)-designated site based on impaired sediment. The site has undergone extensive characterization and provided a site for validation of the SED-FSP capability to delineate potential contaminated sediment areas based on fine grain measurements.

Naval Air Station North Island (NASNI) Installation Restoration (IR) Site 9 is a GSI site where volatile organic compounds (VOCs) are discharging to San Diego Bay. The demonstration leveraged a major characterization study that is scheduled to evaluate alternative remedy technologies and development of clean-up goals. The SED-FSP technology was integrated into the work plan for the IR Site 9 effort and provided an excellent test site for application of the SED-FSP to identify potential groundwater discharge zones.

A contaminated sediment sand cap located at the Anacostia River Active Capping Pilot Study site was also selected for the field demonstrations. At the sand cap location, the ability of the SED-FSP to distinguish and delineate both fine and coarse grain sediments was demonstrated and the capability of the SED-FSP to acquire sub-surface grain size data and obtain grain size vertical profiles was validated.

1.3 REGULATORY DRIVERS

Contaminated sediment and contaminant movement by groundwater–surface water interactions are regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), established to provide a legal framework for cleanup of contaminated sites. At Department of the Navy (DoN) facilities, the Resource Conservation and Recovery Act (RCRA) may also be applied by regulatory agencies for corrective actions at sites or facilities impacted by past treatment, storage, and disposal practices. State and federally regulated sites often have to meet levels such as a Maximum Contaminant Level (MCL) at a point of compliance to protect surface water. In many cases, groundwater in shoreline wells must meet surface water Applicable or Relevant and Appropriate Requirements (ARARs) due to a lack of information or uncertainty regarding modeled dilution and attenuation factors. The Clean Water Act (CWA) TMDL process that sets limits on point and non-point source pollution loading that do not meet, or are not expected to meet, state water quality standards, may also cover contaminant entry points.

2. TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Friction sound is an intriguingly simple and robust technique for in-situ, screening-level measurement of grain size. On a theoretical basis, friction sound is believed to be generated when phonons are produced by the breaking or excitation of atomic or molecular bonds as a contact surface moves over or through a particle matrix. The relationship of friction-sound intensity is a linear function of the radius of particles in contact with the surface and the velocity of the probing surface (Koomans, 2000). Experimental evaluation of acoustic penetrometers for soils showed that the amplitudes of the acoustic emissions from a surface probe moving through or over the soil medium is a function of the median grain size, particle packing, and of the penetration rate of the probe in the soil (Koomans, 2000).

Previous applications employing sound friction for grain size measurement fall into two primary categories: (1) acoustic penetrometers (Muromachi, 1974; Villet, Mitchell, and Tringale, 1981; Tringale and Mitchell, 1982; Menge and van Impe, 1995), and (2) sea-floor sleds (Koomans, 2000). Acoustic penetrometers generally measure the intensity of the friction-sound generated by particles rolling and sliding along the probe surface (Villet, Mitchell, and Tringale, 1981). These systems have been evaluated in a range of applications from traditional cone penetrometers (Tringale and Mitchell, 1982) to soil probes for interplanetary spacecraft (Lorenz et al., 1994). In an application specifically for sediments, Koomans (2000) used a friction-sound sensor for a towed sea-floor geophysical mapping system. Friction between a detector casing and sediment generated friction sound during towing. Field and laboratory data indicated that the amplitude of the sound was primarily a function of the towing speed and the particle size.

The SED-FSP sensor consists of a meter-long, ½-in-diameter stainless steel probe with a tip at the end containing an acoustic microphone (Figure 1). The probe tip is approximately 1¼-in long, screwing into a ¼-in Delrin section that serves to acoustically isolate the microphone from the rest of the SED-FSP assembly. The microphone sensor signal is fed through the probe to an on-board electronics interface package that processes the acoustic signal and transmits the processed data to recording software. The main components of the SED-FSP probe are shown in Figure 2, including the probe tip, Delrin isolator, probe interface, and electronics interface.

The SED-FSP stainless steel probe is coupled to a 5/8-in-diameter pneumatic piston/cylinder drive unit that is vertically mounted onto an aluminum frame assembly (Figure 3). The total height of the system is around 7-½ feet, the frame assembly footprint is approximately 4-foot by 4-foot square. The mechanical interface between the probe and cylinder piston incorporates rubber bobbins as vibration dampeners that further acoustically isolate the drive system from the probe sensor. The pneumatic system is operated with compressed air at a pressure of 85 to 120 psi, controlled by a multiple-valve mechanism controlling the source air pressure to the cylinder. Application of the pneumatic source to the top of the cylinder causes the probe to extend and penetrate the sediment for acquisition of signal. The probe is retracted by directing air pressure to the bottom of the cylinder. The compressed air source can be a portable air compressor on a deployment platform or, for deployments where there are space or utilities limitations, compressed air tanks can be used (e.g., diver tanks used on the Anacostia River).

Figure 1. Probe-tip microphone in Delrin isolator.

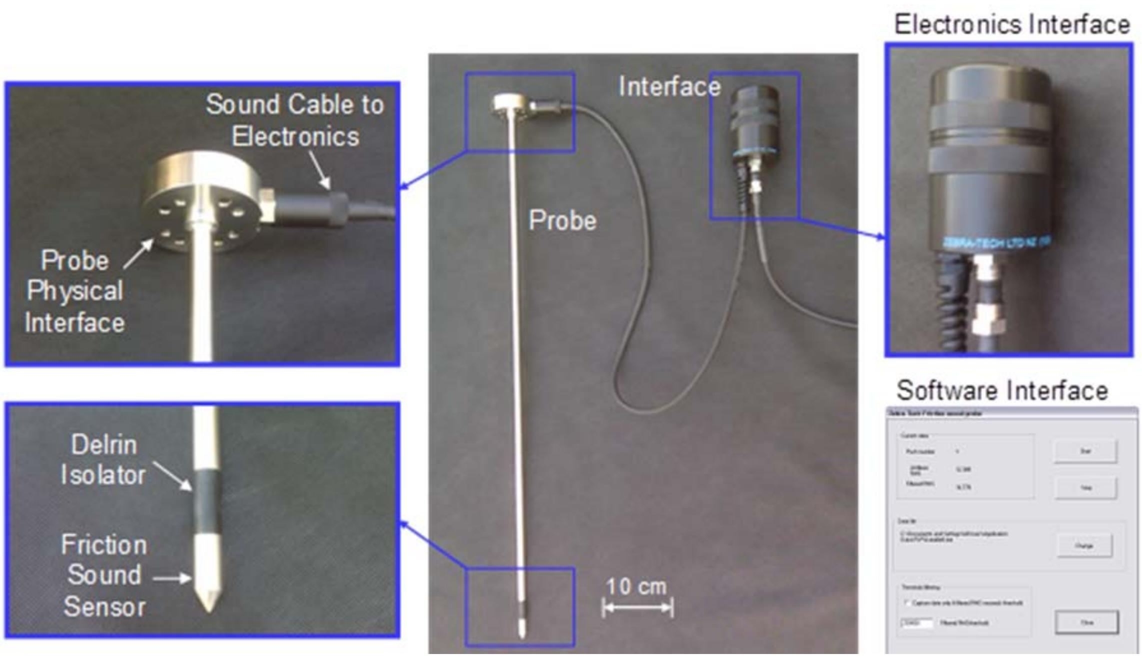

Figure 2. Commercial prototype sediment friction-sound probe (SED-FSP).

When fully retracted the probe tip is near or just in contact with the sediment bed, as the pneumatic cylinder is activated the SED-FSP probe tip extends downward and penetrates the sediment bed at a controlled and constant speed (5.5 to 4.6 cm/sec) to a maximum depth of 2 feet, the full stroke length of the cylinder/piston assembly. An on-board camera mounted on the frame (not shown in the figures) provides real-time video to the operator to ensure that no surface obstructions are present at the deployment location and that the probe is successfully penetrating the sediment bed and not encountering subsurface obstructions. The pneumatic control system is operated at a distance from the SED-FSP assembly from the deck of a boat or other deployment platform.

The video camera also ensures that the probe penetration rate is constant and without interruption. An accurate penetration rate is critical to maintaining calibration of the SED-FSP system and is also used to determine sensor depth; non-constant penetration would cause

errors in calculating depth. Observations of penetration during the three field deployments ensured that the speed of the probe into the bed was constant for nearly all deployments. Situations were encountered where this was not the case, either because subsurface obstructions were encountered or during deployments into very large grained sediments, especially encountered near shore at the NASNI IR Site 9 location. In these cases, the pushes were abandoned and the unit was redeployed. Various methods were investigated to measure actual rate of penetration in real time but these were unsuccessful or found to interfere with operation of the unit. A pneumatic cylinder unit offered by the manufacturer of the SED-FSP cylinder (Bimba Manufacturing) provides a cylinder with electronic output indicating piston extrusion; this addition may be considered for inclusion in the system.

Attached to the feet of the drive system assembly frame are canisters that can hold additional weight to offset penetration resistance of the sediment (see Figure 3). Around 50 pounds of weight (five-pound bags of lead shot) are added onto the system; the canisters can be loaded to a maximum total of 100 pounds, if required. The combined weight of the SED-FSP unit (approximately 40 pounds) and the additional weight require use of a deployment platform with load-handling capabilities. The amount of weight added is site-specific and can change from one station to the next. It is determined on-site by the resistance of the sediment bed to probe penetration, related to sediment texture and compactness.

Users are careful not to over-weight the SED-FSP assembly when deploying on soft sediments. An overweight system will cause the frame to sink substantially into the sediment surface and the probe tip to submerge into the sediment before data acquisition has started. An under-weighted assembly can result in the bed resistance exceeding the penetration force, causing probe penetration to stop and the entire SED-FSP assembly to rise off the bed, risking breakage of the probe/piston interface or even toppling over of the SED-FSP. Real-time observation of the penetration step through the camera system will identify when these conditions occur.

The acoustic signal generated at the probe tip is transmitted to an on-board electronics package that filters microphone output and transmits a processed signal to user-controlled data storage software. Characterization of the SED-FSP unit during production testing confirmed earlier laboratory observations showing that the probe assembly exhibits a characteristic resonant frequency at approximately 2 kHz. To exclude extraneous and background sound from the SED-FSP output, an electronics interface package employs a band-pass filter centered around 2 kHz to reduce signals not associated with SED-FSP generated friction sound. The electronics package captures the microphone output and determines the average root-mean-square (RMS) sound amplitude over a predefined time interval. In the current configuration, the processed signal is output at intervals of 160 msec.

For measurement of surface sediment grain size, the SED-FSP response output associated with the top sediment layer is identified and an average of the responses is calculated. For measurements in subsurface sediments the continuous output of the SED-FSP at 160 msec intervals is correlated to the penetration depth of the probe, yielding friction-sound responses at depth. The SED-FSP electronics package transmits the processed data to a PC laptop computer running FSP-Talk software developed by the SED-FSP commercial developer, Zebra-Tech, Ltd. of Nelson, New Zealand (Figure 2). FSP-Talk saves the processed signal to data files for later processing and displays a plot of the processed signal as a function of time.

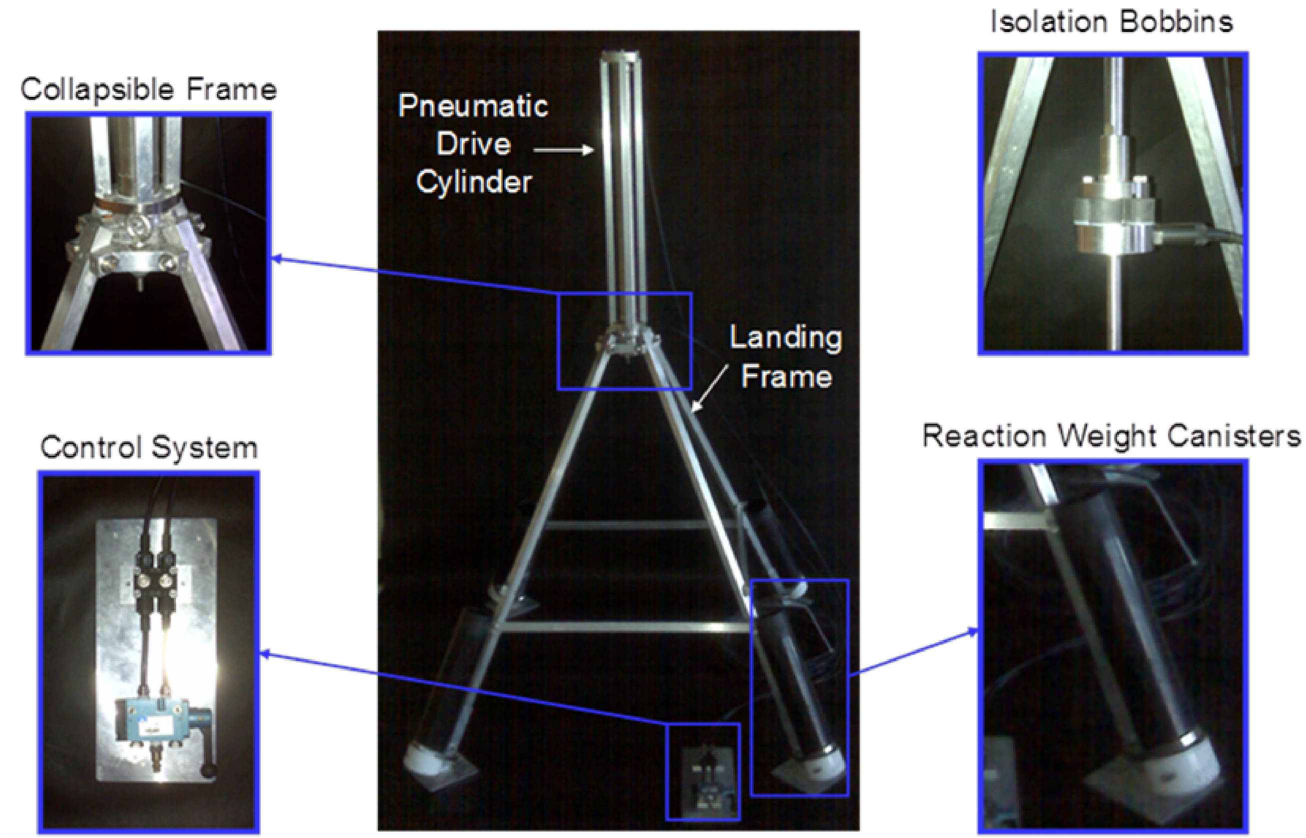

Figure 3. SED-FSP and driving system assembly.

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2.2 TECHNOLOGY DEVELOPMENT

2.2.1 Laboratory Analysis of Prepared Sediments

Development of the prototype SED-FSP stated by characterizing the acoustic response of the unit to laboratory prepared materials of various grain sizes. The size ranges selected corresponded to the Wentworth classifications of particle size diameters (Wentworth, 1922): coarse sand (1000 to 500 µm), medium sand (500 to 250 µm), fine sand (250 to 125 µm), very fine sand (125 to 62.5 µm) and a commercial clay (< 3.9 µm) material purchased from a local supplier. Prepared silt material (62-5 to 3.9 µm) was excluded from the examination due to the difficulty of obtaining or generating a sufficient quantity of material required for measurement. The SED-FSP response for an individual sample measurement is calculated by averaging the acoustical responses for the entire penetration of the probe tip into approximately 12 in of the prepared sediments. The averages of the acoustic intensities for four pushes into each prepared sediment was plotted against the mid-value of the grain size range (e.g., 750 µm for a 1000- to 500-µm sample). The results are plotted in Figure 4; the errors bars on sediment size indicate the sediment grain size range; for acoustic intensities the error bars are standard deviations of four SED-FSP pushes.

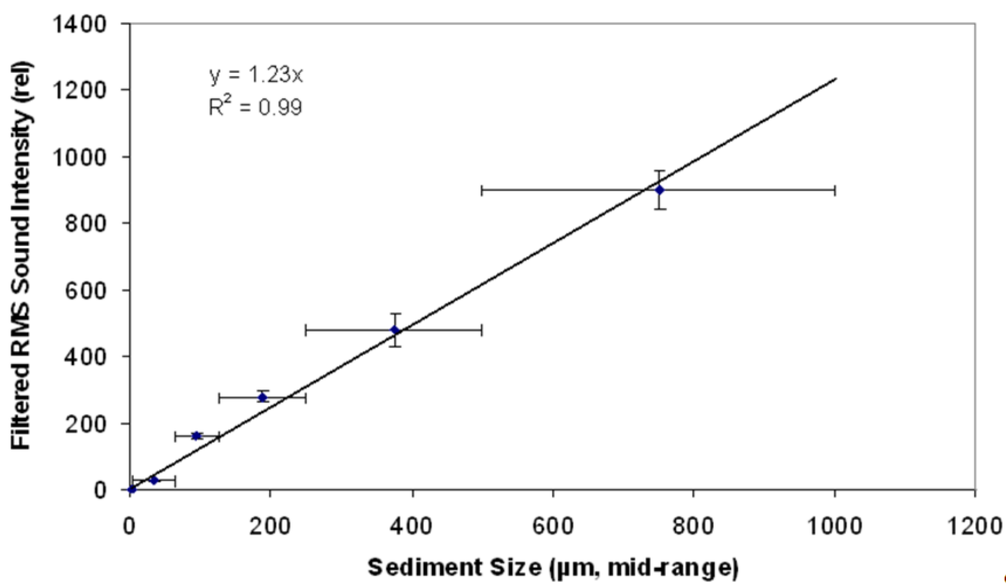

Figure 4. SED-FSP acoustic responses to laboratory prepared samples.

The plot shows that the SED-FSP acoustic response follows a linear relationship over nearly three orders of magnitude of grain size. For the well-sorted sediments the SED-FSP is clearly able to differentiate between the size classes. These laboratory results were used to calibrate acoustic response to grain size for field deployments.

2.2.2 San Diego Bay Sediments

Nine sediment samples were collected from various locations within Mission and San Diego Bays in the San Diego region to evaluate SED-FSP response to actual environmental sediments. Sediments were selected in order to provide a range of sediment types for robust examination of the SED-FSP performance. The sediments were homogenized in the laboratory followed by particle size distribution analysis using a sieve and sedimentation technique (Plumb, 1981). The characteristic grain size used for the comparison is the

graphical mean calculated by averaging the D16, D50, and D84 values that represent the grain sizes (µm) of the 16%, 50%, and 84% cumulative percentiles of the samples by weight. The SED-FSP results are an average of four pushes into the field samples to a depth of approximately 12 in into a container with a 10-in diameter.

In Figure 5, grain size determined by the laboratory calibrated SED-FSP system (y-axis) is plotted against graphical mean grain size as determined by a contracting laboratory by traditional means (ASTM,, 1998). Figure 5 shows that the SED-FSP generated grain size correlated well to the graphical mean grain sizes measured in the laboratory. The results are well correlated over the entire size range with significant deviations from linear seen in the 100- to 300-µm size range. The largest deviation is for the 168-µm mean size sediment that was estimated by the SED-FSP at approximately 95 µm. For the coarser samples the SED-FSP response more accurately depicts measured mean size.

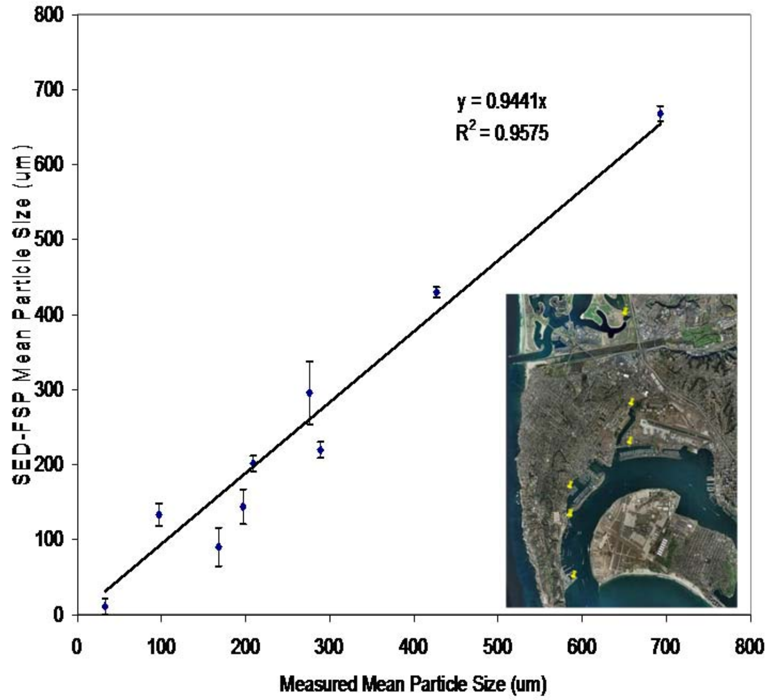

Figure 5. SED-FSP responses for San Diego area sediments.

2.2.3 Vertical Profile Capabilities

Figure 6 is the representation of the vertical profile recorded by the SED-FSP in a prepared sample of mixed layers of very fine sand (63 to 125 µm) over medium sand (250 to 500 µm). The SED-FSP calibrated responses are the averaged results for five pushes into approximately 12 in of sample. Included in the plot is the mid-range grain-size value for the very fine sand (94 µm) and medium sands (375 µm). The interface between the sample layers is abrupt, while the SED-FSP portrays a gradual change. But within the layers, the SED-FSP indicated a differentiation of material type; the results demonstrated the ability of the SED-FSP to delineate the different sized strata in the prepared sample. This utility will be demonstrated at a thin-layer cap site where large sized sand particles have been distributed over finer grained native sediments.

2.3 PENETRATION FORCE MEASUREMENT

During progression of the project, it was observed that measurement of penetration resistance could be readily incorporated into the SED-FSP system to provide information that could potentially complement the friction-sound data. Dependence or association of penetration resistance to grain size had not been investigated but it was determined that penetration resistance would be complementary data and could be incorporated into the unit with little effort.

Between the second and third field deployments, additional components were developed for incorporation into the SED-FSP system to measure the resistance to penetration encountered at the sediment bed. The SED-FSP manufacturer (Zebra-Tech, Ltd.) developed a module interface that is inserted into the input and output air lines of the pneumatic cylinder. The interface contains two pressure transducers that measure the pressure at the driving cylinder input and output and internally determines the net pressure applied to the probe sensor. Figure 7 shows the air source line connections to the driving cylinder (left) and the interface module unit attached to the assembly frame (right, upper interface module). The module transmits the pressure differential at 160-msec intervals to the PC running the FSP-Talk software, which acquires and records the data.

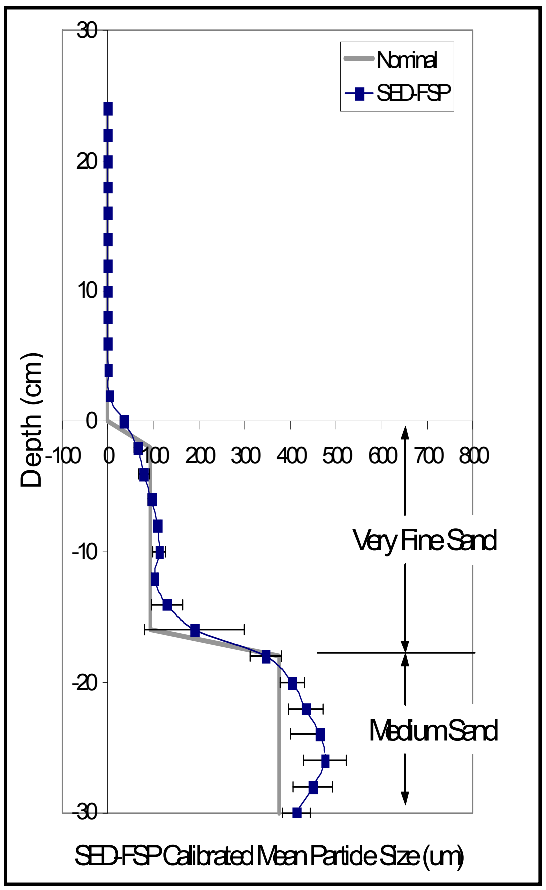

Figure 6. SED-FSP grain size measurements for a prepared, layered sediment.

Association of the differential pressure measurement to penetration resistance force was made using the laboratory setup shown in Figure 8. A setup was devised that used weights to provide resistance to the downward penetration stroke. A simple pulley system attached to the probe tip on one end and free-hanging weights on the other was used to provide known resistances. As the probe was extended (analogous to penetration stroke) and the weights lifted, the differential pressure was recorded by the FSP-Talk software. The resulting pressure differentials were analyzed and plotted against the known weights; the results are shown in Figure 9.

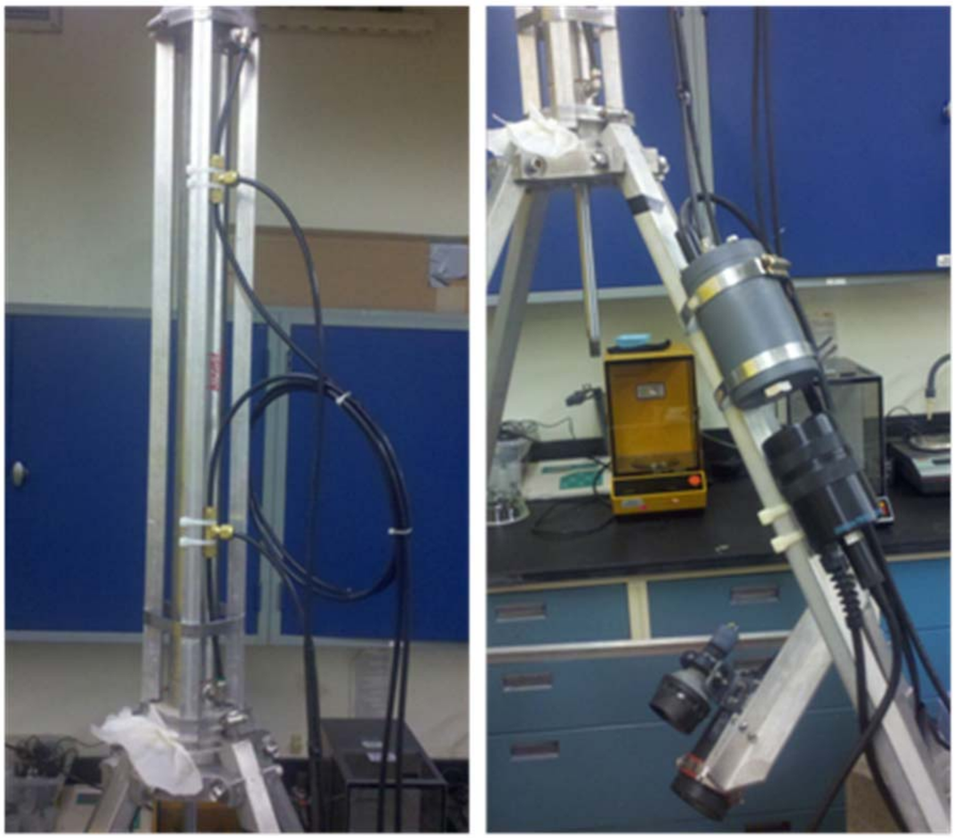

Figure 7. Pneumatic source line "T's" from the drive cylinder input and output ports to the pressure measurement module (left-side photo) and pressure measurement interface module attached to SED-FSP frame (right-side photo). Note also, in the right-side photo, the friction-sound interface module and the on-board video camera and light.

The data plot (Figure 9) shows very good correlation between the resistance weights applied to the probe and the pneumatic pressure differential. Each of the data points is the average of 4 pushes, including standard deviations of the measurements represented as the vertical error bars.

Examination of the chart shows that for resistances less than 20 pounds the pressure applied for downward movement of the piston against the resistance weights is negative. This is also indicated by a negative pressure of 8.45 psi (y-intercept) at 0 pounds resistance. This is counter-intuitive because a negative pressure indicates that the pressure at the output air line (i.e., bottom portion of the cylinder) is greater than the source line; the piston should therefore be moving in an upward direction. The cause is twofold; one is due to the weight of

the piston and the shaft assembly. The weight is additional force in a downward direction not accounted for during calibration. The other reason is due to the internal construction of the cylinder assembly. The top piston surface area, onto which the input pressure is applied to produce downward force, is greater in surface area than the bottom piston surface that includes the attachment of the cylinder shaft. The surface area differential results in greater pressure required in the bottom of the cylinder than at the top to generate an equal force and therefore the discrepancy seen in the calibration chart.

Figure 8. Pressure measurement calibration setup.

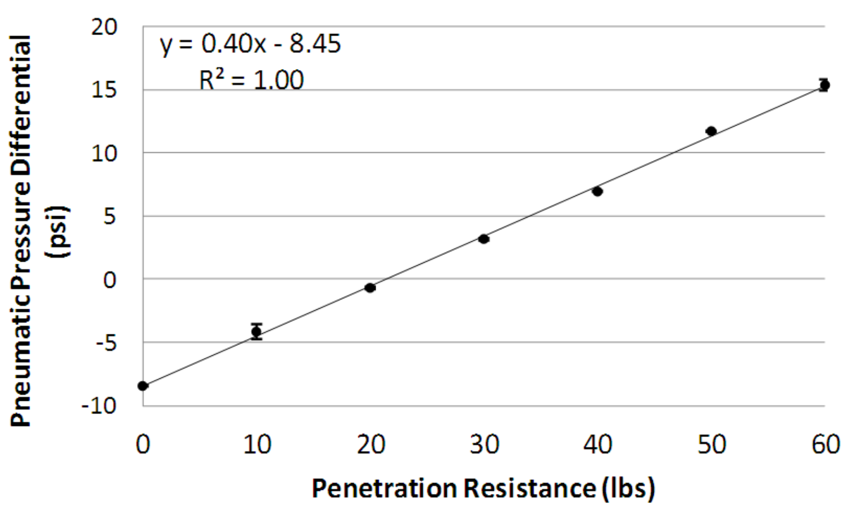

Figure 9. Pressure measurement calibration results.

2.3.1 Field Demonstration: Penetration Force Measurements

Figure 10 displays differential pressure measurement output by the SED-FSP for a laboratory calibration run (left) and during the third field deployment. The horizontal axis is time (seconds) the vertical axis is differential pneumatic pressure (psi). The laboratory

calibration data is four runs against a load of 30 pounds; the plot shows the reproducibility of the process and capability of the measurement hardware to output consistent results.

During phase A (blue shaded area) of the run, the SED-FSP system is fully retracted, the pneumatic source is directed to the bottom of the cylinder, and the top is open to ambient pressure. The pressure differential output by the interface unit is ambient pressure minus the source pressure, approximately -110 psi. The piston is fully retracted until the beginning of phase B at which time the pneumatic source is diverted to the top of the cylinder and the bottom is opened to ambient. The ramp-up in phase B indicates that the top of the cylinder has started filling with air and pressure is increasing relative to the bottom of the cylinder; the net pressure therefore becomes less negative. During phase C, the cylinder piston moves downward against 30 pounds of force; at the end of phase C, the piston has extended to its full length. Phase C pressure is averaged and indicates pressure required to "push" against 30 pounds. This data is used in the plot in Figure 9, including similar data for other known resistance weights.

The SED-FSP pressure measurement capabilities were taken into the field during the deployment at the Anacostia River sand cap location. The chart on the right of Figure 10 below shows the results of deployment at a single station. These data are consistent for all stations that were acquired. The results indicated the unit is not working correctly, resulting in the faulty signal. Also of note is that the starting pressure at approximately 50 psi incorrectly indicates the 90- to 95-psi source pressure that was used for the deployment. The data will not be further analyzed but attempts will be made to identify and correct the issue, and during future deployments the system will be evaluated for applicability of the measurement to sediment properties.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.4.1 Advantages of the Technology

The development of this capability provides at least three significant advantages over current approaches. First, potential cost savings could be associated with the ability to quickly and easily map grain size distributions. The cost savings stems from the reduced sampling time, sample handling, sample shipping, and sample analysis efforts. Second, obtaining data while in the field creates the opportunity for adaptive sampling in accordance with TRIAD and other adaptive management principles, leading to a strong potential for more focused and thus less expensive characterization for both contaminated sediment and GSI sites. Third, the ability to rapidly obtain vertical profiles of grain size provides the potential to cost effectively assess the implementation and stability of certain sediment remedies such as thin-layer caps and amendments that have distinctive grain size properties relative to the native sediment. Thus, specific advantages of the SED-FSP over traditional grain size analytical techniques include:

- Rapid, cost effective, in-situ grain size surveys of bottom sediments for particle sizes ranging from coarse sand to silt/clay,
- Support for adaptive management strategies such as TRIAD to streamline site characterizations,
- Improvements in cost and efficiency associated with the ability to rapidly characterize the implementation and stability of certain sediment remedies such as thin-layer capping.

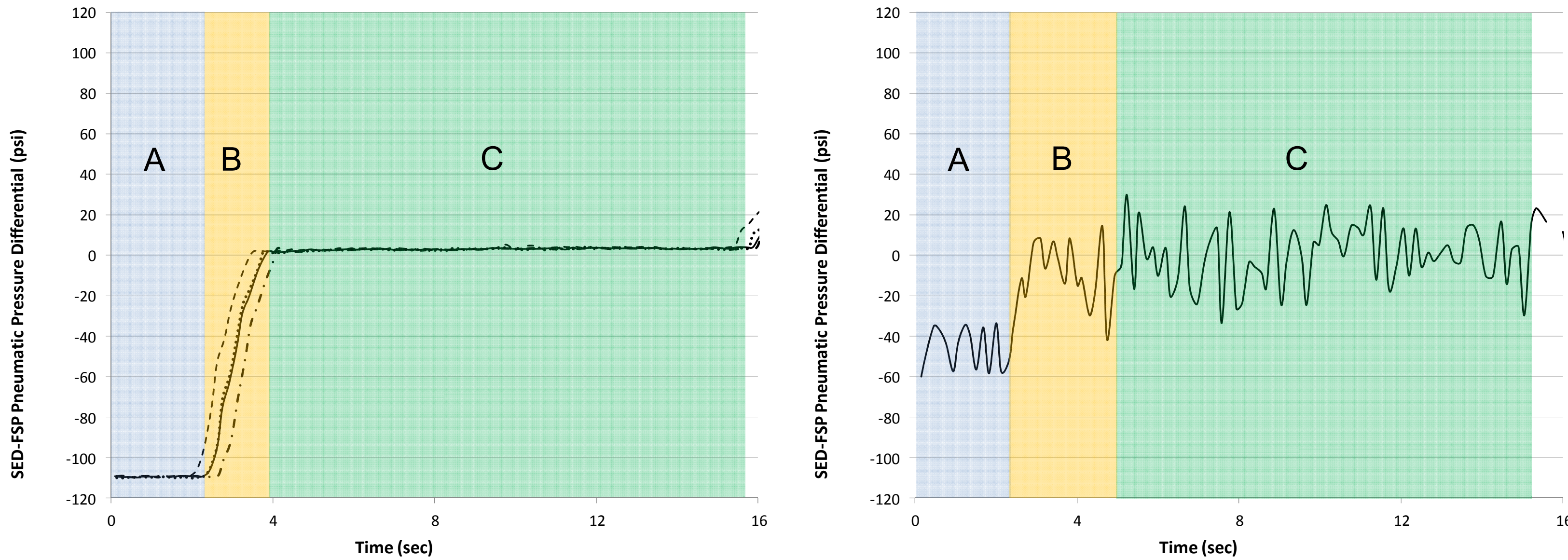

Figure 10. SED-FSP pressure measurement data for a laboratory calibration (left) and a field deployment at the Anacostia River sand cap site at station AR-03.

2.4.2 Limitations of the Technology

Potential technical risks identified in association with field demonstration and commercialization of the SED-FSP technology include:

- The SED-FSP system output is limited to a single characteristic indicator of grain size; a size distribution or other statistical parameters are not measured. The output value is mean grain size diameter or an associated size classification (e.g., Wentworth size class).
- Calibrations with site sediments are required. Current experience indicates that a laboratory-calibrated SED-FSP will underestimate grain size during field deployments.
- Controlling for deployment effects such as non-uniform push velocity and background noise.

During testing, the SED-FSP sensor response was found to correlate very closely to the mid-range grain size of prepared, sieved sediments (well sorted) that were used as standards. The laboratory-calibrated SED-FSP, when deployed in the field, consistently underestimated grain size when compared to laboratory-validated data. The solution was to field calibrate the SED-FSP to site sediments. A global empirical calibration from the three demonstration sites may prove robust enough to use across other sites.

The push velocity issue was addressed by developing the drive system assembly described in Section 2. The pneumatic drive generally provides sufficient force to penetrate the sediment bed surface at a constant rate. On multiple occasions, usually near shore in very coarse sand, the penetration stroke was slowed considerably and even stopped, resulting in redeployment or even abandonment of the site.

Background noise has not been a significant factor in laboratory testing; field tests determined that background noise levels are not significant relative to friction sound in the filtered 2-kHz band.

3. PERFORMANCE OBJECTIVES

Performance objectives are the criteria that provide the basis for evaluating the success of the technology. The performance objectives for the project are shown in Table 1. The objectives focus on rapid in situ classification of surface sediment type (quantitative) over a broad range of applications and conditions (qualitative). The quantitative performance will be assessed by direct comparison of SED-FSP response to results of grain size analysis by a contracting laboratory using a standard method. The qualitative performance will be assessed through assessment over three varying application regimes.

Table 1. Performance objectives for the SED-FSP demonstration.

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objective		
Rapidly classify surface sediment substrates in-situ	SED-FSP friction sound data and corresponding PSD data over a range of sediment types.	SED-FSP correctly classifies sediments based on particle size statistics.
Qualitative Performance Objective		
Demonstrate applicability for a range of potential applications.	Calibrated SED-FSP friction sound data over a range of different applications including GSI, contaminated sediment and thin-layer cap.	SED-FSP data useful in delineating the extent of discharge, contamination, and/or cap placement.

3.1 OBJECTIVE 1 – RAPIDLY CLASSIFY SURFACE SUBSTRATES IN SITU

The effectiveness of the technology is a function of the degree to which the sediment substrate can be rapidly and accurately classified.

3.1.1 Data Requirements

The data requirements for this objective are the calibrated output of the SED-FSP response and the verified grain size obtained by laboratory analysis of the corresponding sediments. The corresponding sediment samples were collected by a diver using standard coring methods, ensuring that the SED-FSP probe deployment and the sediment samples were collocated. The sediment samples were submitted to a contracting laboratory for particle-size distribution (PSD) analysis according to ASTM D422, Standard Test Method for Particle-Size Analysis of Soils. Based on the resulting graphical mean grain size, the sediments were classified according to the Wentworth scale of sediment grain size classification (Wentworth, 1922). The calibrated SED-FSP grain-size response was used to obtain a corresponding Wentworth size classification.

3.1.2 Success Criteria

Quantitative success was determined based on the SED-FSP ability to correctly classify sediments based on mean grain size. Specific measures of classification success included reliability, efficiency, and specificity. Reliability measures the percentage of correctly classified stations in comparison to the total number of stations. For each grain size classification level (sand, silt, clay), efficiency measures the percentage of correctly classified stations in that classification level in comparison to the total number of stations classified in that level. Similarly for each classification level, the specificity measures percent of correctly

classified stations in that level out of the total number of stations that actually fall in that level. The project goals for reliability, efficiency, and specificity were 80%.

3.2 OBJECTIVE 2 – DEMONSTRATE APPLICABILITY FOR A RANGE OF POTENTIAL APPLICATIONS

The relevance of the technology to DoD depends to a large degree on the range of applicability over a range of site characteristics and conditions.

3.2.1 Data Requirements

The data requirements for this objective required SED-FSP demonstration over a range of different applications including a GSI site, a contaminated sediment site, and a thin-layer cap site. For GSI sites, the probe differentiated coarse-grain units that represent potential preferential groundwater flow pathways. For contaminated sediment sites, the probe delineated areas of high fines content, which are generally co-associated with high contaminant levels. At the thin-layer cap site, the probe was used to profile the location and thickness of the capping material and evaluate the stability of the cap based on overall thickness and mixing with the underlying native material.

3.2.2 Success Criteria

Qualitative success was determined by the ability of the SED-FSP to provide a site survey map of grain size or similar information to delineate the extent of potential discharge zones, extent of potential contamination, and/or cap placement and stability as determined by comparison to results obtained by standard methods of PSD analysis of sampled sediments.

4. SITE DESCRIPTION

Demonstration site selection was based on meeting the performance objectives of demonstrating performance over a range of grain size conditions, ranging from predominantly sandy to predominantly fine. Sites were chosen that have significant historical characterization data or where there were on-going studies to leverage mobilization, deployment, and other costs. Finally, site selection was based on spanning the three application regimes: contaminated sediments, a GSI zone, and a remedy placement (thin-layer containment cap).

4.1 SITE LOCATION AND HISTORY

The sites selected for the technology demonstration were Naval Air Station North Island (NASNI) - Installation Restoration Site 9 (GSI), Naval Base San Diego – Chollas Creek (contaminated sediment), and a contaminated sediment sand cap at the Anacostia River Pilot Cap Study site in Washington, D.C.

4.1.1 Installation Restoration Site 9 - Naval Air Station North Island

Naval Air Station North Island Installation Restoration Site 9 (IR Site 9) has been identified as a GSI site where VOCs are discharging to San Diego Bay (BNI, 1998). This demonstration project was integrated into the work plan of a broader characterization study scheduled to evaluate alternative remedy technologies and development of cleanup goals (NAVFAC SW, 2009). IR Site 9 is a former Chemical Waste Disposal Area located in the southwest portion of NASNI (Figure 11). The site operated as a chemical waste disposal area from the late 1940s through the mid-1970s. All chemical wastes from NASNI industrial operations, including paints, solvents, caustics, acids, and oils that were not disposed at alternate NASNI disposal sites were disposed of at IR Site 9. No records were kept of the amounts of chemicals disposed; a 1978 estimate of wastes indicates that an estimated 8 million to 32 million gallons of wastes were disposed at IR Site 9 (NAVFAC SW, 2009).

In accordance with current Navy policy, the Navy has determined that it will revise remedial alternatives for IR Site 9 that were previously evaluated in a 2003 feasibility study (FS) (BEI, 2003). A characterization study will be performed to acquire additional soil and groundwater data necessary to satisfactorily evaluate remedial technologies and develop cleanup goals supporting an updated FS. The study will address the acquisition of additional site data for identifying soil and groundwater data gaps, defining the sampling and analyses required to characterize the current nature and extent of contamination in soil, and refining the understanding of groundwater–surface water interactions. The SED-FSP deployment survey will complement data obtained by the Trident Probe and Ultraseep systems to provide evidence for identifying and characterizing groundwater discharge zones.

4.1.2 Mouth of Chollas Creek TMDL Site - Naval Base San Diego

In 1989, the California State legislature established the Bay Protection and Toxic Cleanup Program to provide protection of present and future beneficial uses of the bays and estuarine waters of California and to identify and characterize toxic hot spots (THS), including planning for their cleanup or other remedial actions. The State Water Resources Control Board developed a Regional Toxic Hot Spots Cleanup Plan (SDRWQCB, 1998) for the San Diego Region; in that plan they identified the mouth of Chollas Creek where it enters into San Diego Bay (Figure 12) as a THS, having contaminated sediments and aquatic life impacts. The toxicity observed in Chollas Creek led the Regional Water Quality Control Board to add this watershed to the CWA 303(d) list of impaired water bodies. All water

bodies on the 303(d) list are subject to a TMDL. The TMDLs attempt to control water quality problems associated with multiple sources of constituents including non-point sources such as Chollas Creek. The objective of the TMDL approach is to address the cumulative loads that may be environmentally safe when taken individually, but can result in water quality problems when combined together.

Chollas Creek has undergone extensive characterization and is known to display strong gradients in both sediment substrate type and contamination levels. Historical data shows that the primary contaminant sources and pathways are the discharge of contaminants from the near shore into the surface waters and their eventual settling into the sediments. Existing data from the THS and TMDL studies are available to leverage the SED-FSP effort and will provide a strong site for evaluation of the SED-FSP to delineate potential areas of contaminated sediment based on high fines content.

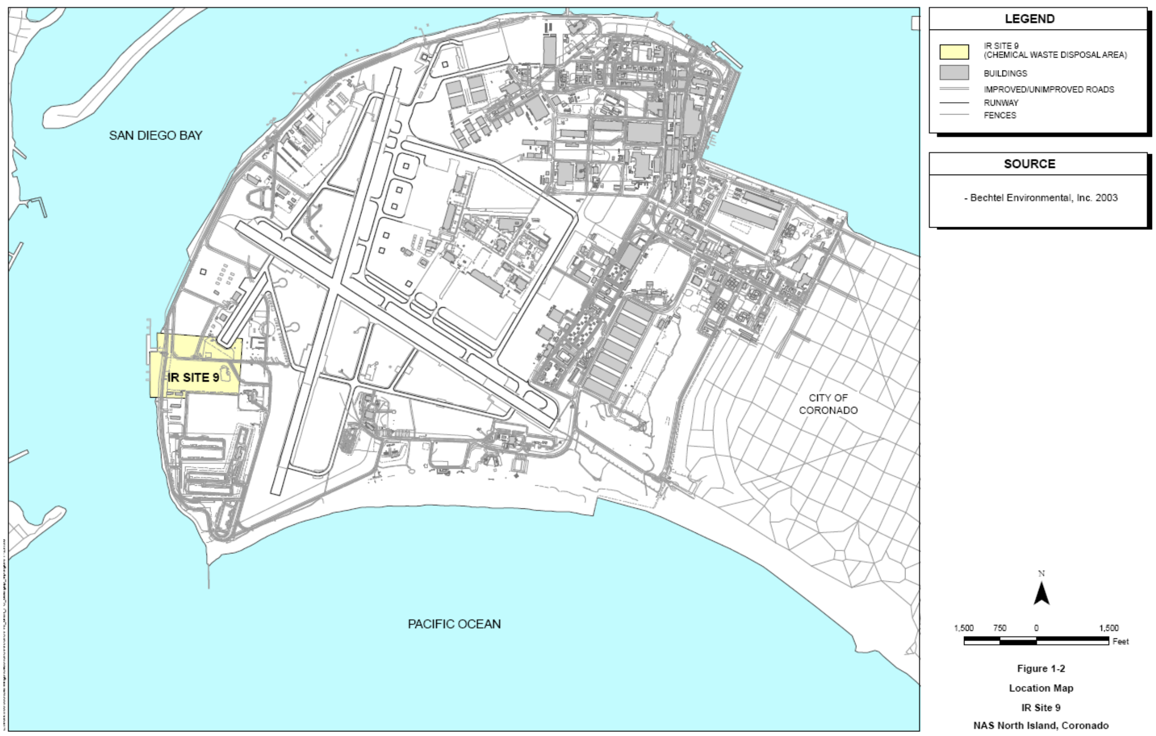

Figure 11. Installation Restoration Site 9 at Naval Air Station North Island.

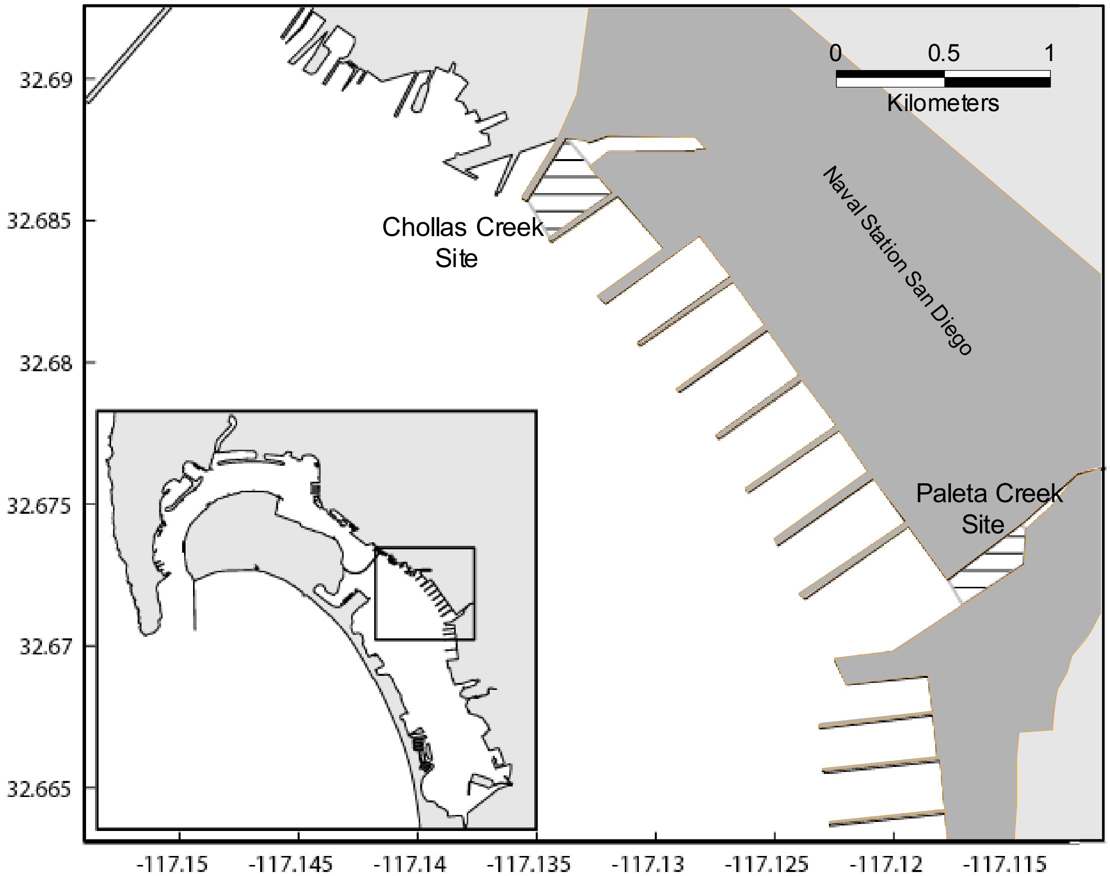

Figure 12. Chollas Creek site, NBSD.

4.1.3 Anacostia River Active Capping Pilot Study Site, Washington, D.C.

The Anacostia River, located in Maryland and the District of Columbia, has been identified as one of the 10 most contaminated rivers in the country and also one of three areas of concern for the Chesapeake Bay. Historic industrial, municipal, and military activities have resulted in toxic levels of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), metals, and other contaminants. In March 2004, innovative contaminated sediment cap materials were placed in the Anacostia River to demonstrate their applicability for management of sediment contaminants (Figure 13). Following extensive site characterization and laboratory treatability studies, three active capping material technologies were selected: AquaBlock, apatite, and coke breeze in a laminated mat. A thin-layer sand cap was included for comparison to a traditional remedy. The goal of the capping project was to provide site-specific preliminary design information on the application of innovative technologies where historic industrial, municipal, and military activities have resulted in potentially hazardous levels of contaminants.

The project is an integral part of efforts led by the Anacostia Watershed Toxics Alliance (AWTA) to improve water quality and restore the river. The project was implemented by a team led by Louisiana State University, the AWTA, and its members. The USEPA Superfund Innovative Technology Evaluation (SITE) program provided extensive support as part of a complementary study of AquaBlok, a bentonite-clay material used as an impermeable barrier over the contaminated sediments. All materials, except coke, were placed in 8000-sq-ft test

plots during March and April 2004. Because of concerns related to settling and dispersion of the material, coke was placed as a 1.25-cm layer in a laminated mat. The sand cap, located on the northeast corner of the study area, was selected for demonstration of the SED-FSP technology.

Figure 13. Anacostia River Active Capping Pilot Study Site, Washington, D.C.

4.2 SITE GEOLOGY/HYDROGEOLOGY

4.2.1 Installation Restoration Site 9 - Naval Air Station North Island

IR Site 9 comprises approximately 50 acres, measuring around 1200 by 1800 ft. Approximately 75 percent of the area within the site boundary is unpaved sand (predominantly dredged bay sands) with partial vegetative growth. NASNI groundwater communicates hydraulically with the saline waters of San Diego Bay and the Pacific Ocean and with freshwater on the eastern side of NASNI and the city of Coronado. The freshwater lens is recharged by irrigation water from the city of Coronado and NASNI (BNI, 1998). Tidal fluctuations average 5.6 ft between mean lower low water and mean higher high water. Bay tides in the bay are mixed, with two low tides of different heights and two high tides of different heights each day.

Modeling and measurements indicate that VOCs are migrating into San Diego Bay from groundwater sources originating at IR Site 9. Previous measurements of pore water at 13 offshore stations (Figure 14) at IR Site 9 indicated that elevated levels of VOCs are present in a tightly restricted area near the southern reach of Bravo Pier (SPAWAR, 2001). Highest levels were always observed at the deepest measurement points (5 ft vs. 1 ft below bay

bottom; Figure 14), indicating that the concentrations are significantly attenuated within the sediment before entering the bay. In addition, the primary VOCs observed were 1,1-DCE, 1,2-DCE, and VC, indicating that limited degradation of the Trichloroethylene (TCE) source product is occurring before the material reaches the bay. The SED-FSP system has been integrated into the sampling and analysis plan for a characterization study at IR Site 9.

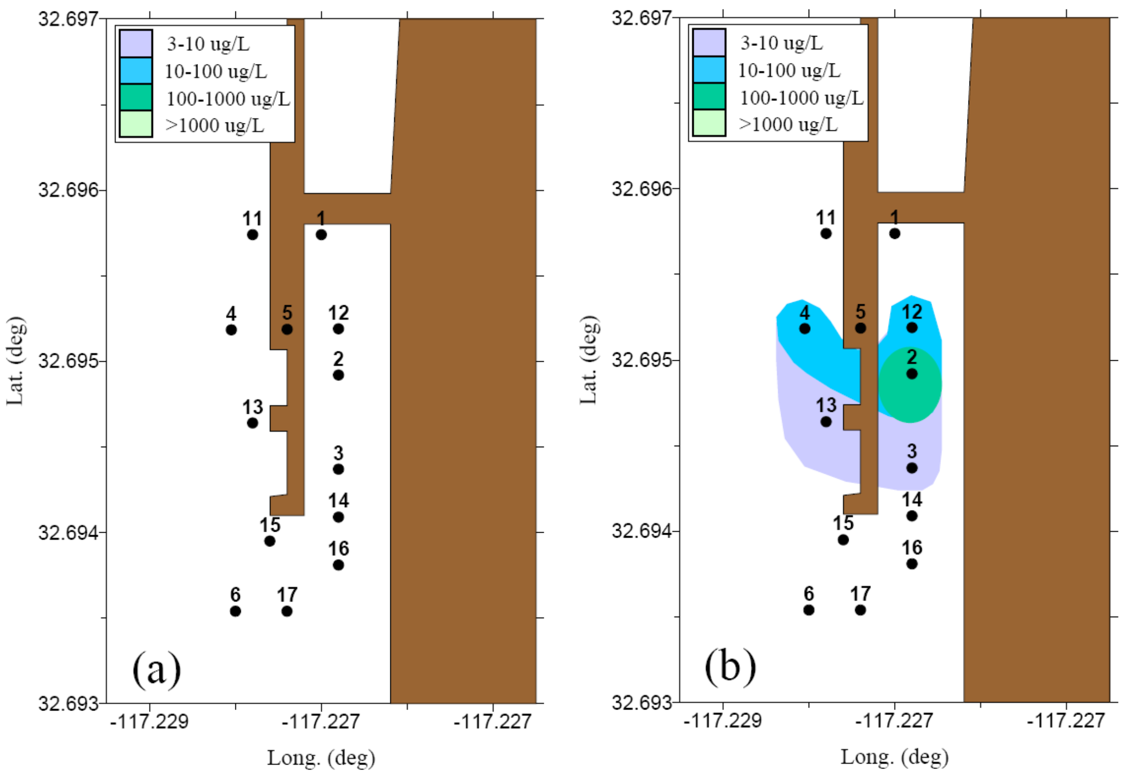

Figure 14. Porewater distribution of trans-1,2-DCE at 1 ft (a) and 5 ft (b) depths from the 1999–2000 porewater survey at IR Site 9.

4.2.2 Mouth of Chollas Creek

In support of the Regional Toxic Hot Spots Program, an assessment of the mouth of Chollas Creek was conducted by SSC Pacific in July and August 2001 (SCCRWP, 2005). In addition to sampling for chemical contaminants and biological effects, samples were collected and analyzed for grain texture. Fourteen sampling locations were selected, approximately evenly distributed within the Chollas Creek mouth site bounded by the National Steel and Shipbuilding Company to the north and Pier 1 of Naval Base San Diego to the south (Figure 15). The total area covered by these stations is 100,600 m^2, thus each sampling site was roughly representative of 7200 m^2 or approximately 1.8 acres. Eleven of the stations were outside of the creek, in San Diego Bay, and an additional three stations were in the inner portion of the creek area. Water depths at the Chollas Creek stations ranged from 2.4 to 10.8 m, with the shallowest water at the inner creek area at C14 and the deepest water near the pier head at C03.

Table 2 shows the results for grain texture analysis by a combined sieving and pipette technique, yielding grain size classes for gravel (4 to 2 mm), sand (2 to 0.0625 mm), silt (0.0625 to 0.0039 mm), and clay (< 0.0039 mm). Included in the table are values for fines,

the fraction of sediments smaller in size than 0.063 mm that include silts and clays. For all samples collected, the smallest fines percentages were measured at the mouth of the creek at locations C07, C08, and C11, and generally increase in a direction towards San Diego Bay. The trend of decreasing grain size is also seen moving away from the mouth into the creek; the largest percentage of fines for all of the locations was measured for C14, the sample furthest into the creek. Conditions at the Chollas Creek site were well suited for demonstrating the capability of the SED-FSP to identify areas of high fines content using associated with areas of high contaminant concentrations.

4.2.3 Anacostia River Active Capping Pilot Study Site, Washington, D.C.

The Anacostia River is a freshwater tidal system draining an urban watershed encompassing 176 square miles in Maryland and the District of Columbia. Tidal amplitudes in the area range from 1 to 2 ft, the river currents are normally driven by tidal fluctuations. The area is relatively featureless and exhibits a gentle slope with water depths ranging from approximately 5 to 20 ft. The capping study site was chosen because it was outside of the navigational channel in a slow flow segment of the river, and had a minimal slope (<4%). The native sediment at the site has a 3-m layer of high plasticity silty clay that is soft, weak, and compressible. This is underlain by a 1.5-m thick layer of silty clayey sand (Horne Engineering Services, Inc., 2004).

The field demonstration was conducted on the sand cell section of the study area located on the northeast portion of the site (refer to Figure 13). The sand cap layer thickness was targeted at 12 in; after initial placement, surveys of the caps showed that actual thickness average was 8.9 ±3.2 in, ranging from 0.25 ft at the edges to 1.25 ft in the southwest portion of the cell (Ocean Surveys, 2004). Assessment surveys of the AquaBlok cap continued for 30 months (October 2006) after placement as part of USEPA's SITE program. Bathymetric surveys of the sand cell were conducted 1 and 6 months after placement (Figure 16); additional site characterizations have not occurred.

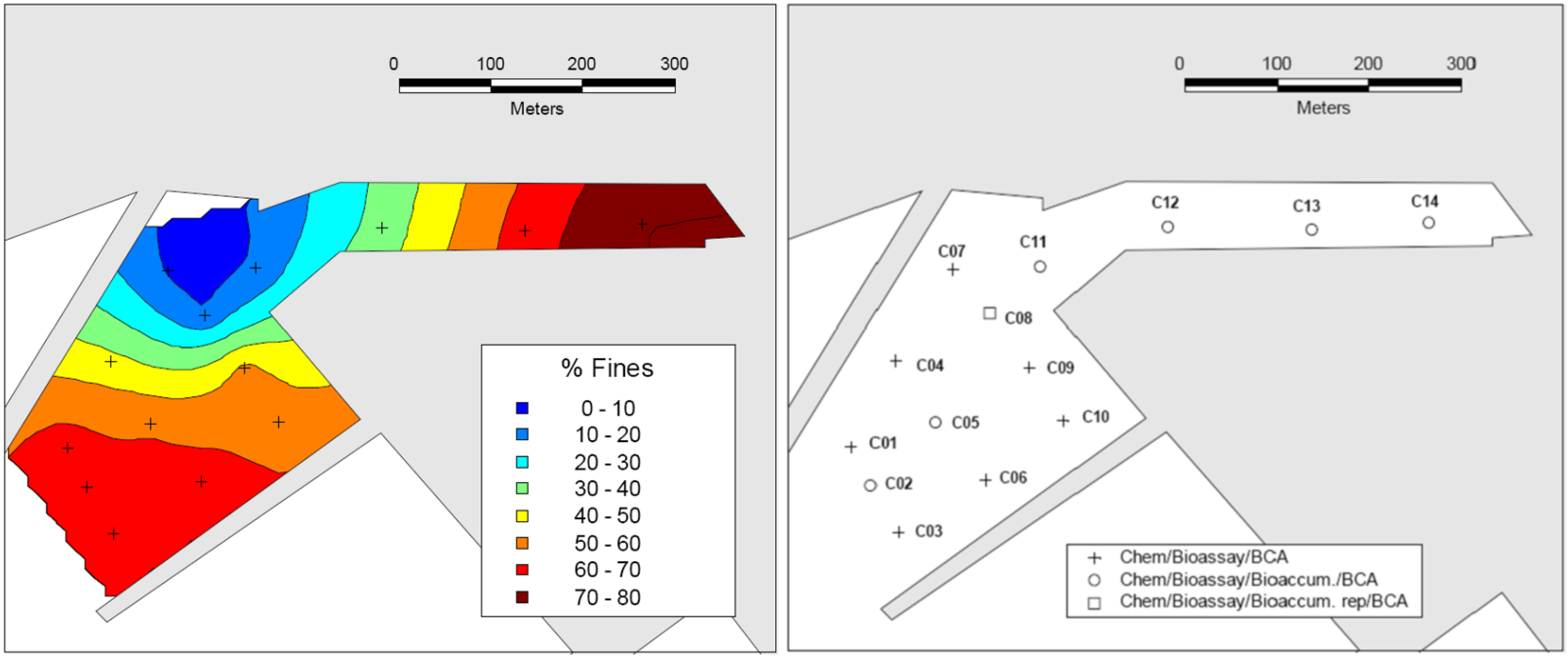

Figure 15. Mouth of Chollas Creek sampling locations and fines distribution (2001).

Table 2. Chollas Creek grain size results in support of TMDL study (SCCRWP, 2005).

	C01	C02	C03	C04	C05	C06	C07
Gravel (> 2 mm), %	0.04	1.55	1.07	1.47	0.12	0.97	0.85
Sand (2 - 0.0625 mm)	34.92	37.09	36.91	55.38	41.52	35.45	89.92
Silt (0.0625 - 0.0039 mm)	31.69	28.98	29.27	21.20	30.21	29.80	4.43
Clay (<0.0039 mm)	33.34	32.38	32.75	21.95	28.16	33.78	4.80
Fines (<0.0625 mm)	65.03	61.36	62.02	43.15	58.37	63.58	9.23
	C08	C09	C10	C11	C12	C13	C14
Gravel (> 2 mm)	2.57	0.12	1.24	3.41	0.18	0.00	0.05
Sand (2 - 0.0625 mm)	86.54	46.88	45.07	84.95	66.04	35.32	20.20
Silt (0.0625 - 0.0039 mm)	5.46	26.15	25.16	5.89	18.41	35.09	40.12
Clay (<0.0039 mm)	5.44	26.85	28.53	5.76	15.37	29.59	39.62
Fines (<0.0625 mm)	10.90	53.00	53.69	11.65	33.78	64.68	79.74

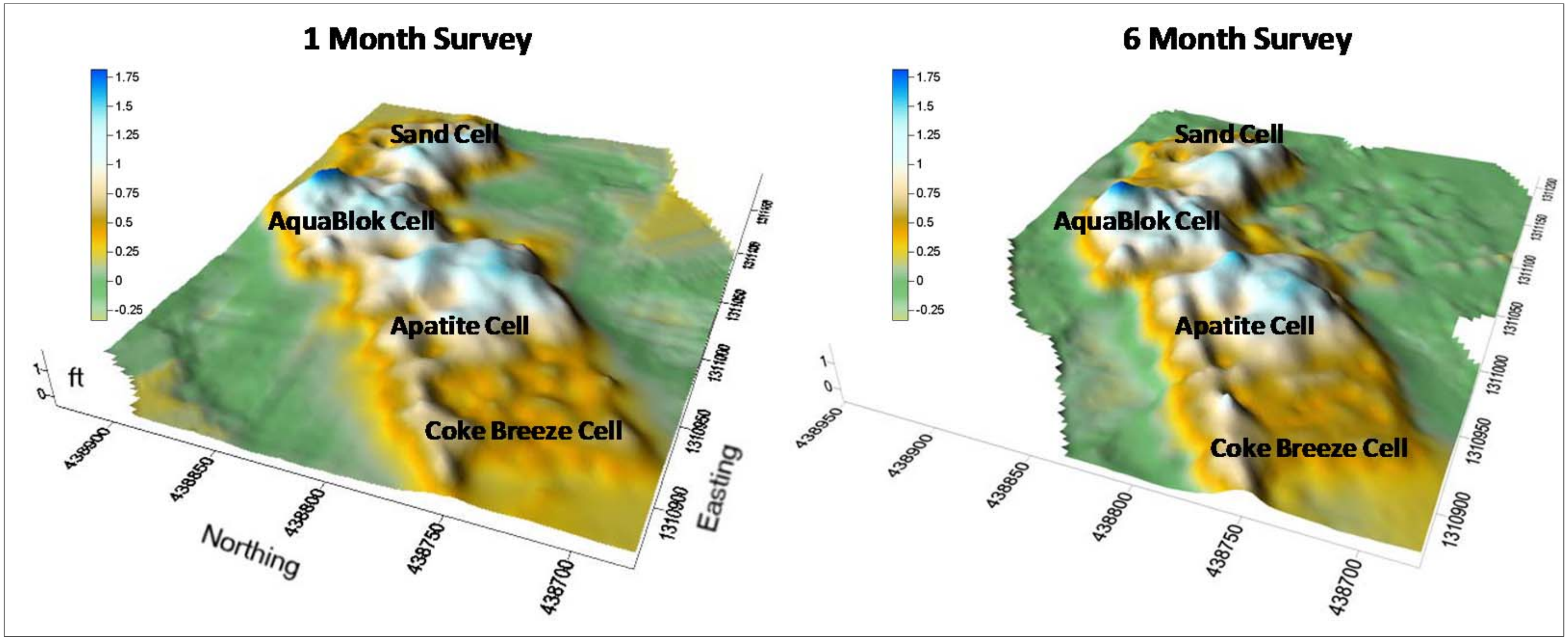

Figure 16. Anacostia River Pilot Cap Study site bathymetric survey results, 1 month and 6 months (Ocean Surveys, 2004).

5. TEST DESIGN

5.1 EXPERIMENTAL CONCEPTUAL DESIGN

The objective of this project was to assess the effectiveness of the SED-FSP for in-situ measurement of grain size over a broad spectrum of sediment grain size conditions. The SED-FSP performance was assessed by comparison of the SED-FSP output to verified laboratory grain size measurements over a range of sediment types at three application regimes: a contaminated sediment site, a groundwater–surface water interaction site, and a thin-layer cap site.

5.2 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The SED-FSP probe unit is self-contained, requiring a deployment platform where a compressed air source, power source, and an operator with laptop computer and video monitor are located. The deployment vessel used for the NBSD Chollas Creek and IR Site 9 locations was a 40-ft survey vessel belonging to the Environmental Sciences and Applied Systems Branch (Code 71750) of SSC Pacific. At the Anacostia River site the deployment platform was a 16-ft x 8-ft pontoon platform with a 12-ft recreation boat rental for support. Load-handling capabilities are required to deploy the SED-FSP from the platform; at the Anacostia River location, this was a 6-ft davit with a hand-crank. With the exception of a power system and compressed air source, no other components are required to operate the system.

5.3 FIELD TESTING

Field testing of the unit was largely independent of the demonstration site location and characteristics. Deployments at the three demonstration sites were similar, differing in number of pushes and depth of implementation.

5.3.1 Field Mobilization

Field mobilization includes calibration, packing and shipment of the SED-FSP, the drive system, and components. For the field demonstrations at Chollas Creek and IR Site 9, shipping was not required; transit to the site was directly from the SSC Pacific laboratory. For the field demonstration at the Anacostia River location, the entire SED-FSP unit was shipped in two 5-ft x 5-ft x 3-ft shipping crates. A pontoon vessel was also shipped to the Anacostia River location and constructed on site. For future deployments, it is recommended that a vessel of appropriate capabilities be rented locally.

SED-FSP system assembly is accomplished within 2 hours from start to finish. The system is assembled by attaching the pneumatic cylinder assembly and the load bearing canisters to the drive system frame. The probe and interface are attached to the cylinder piston and the electronics and pneumatic pressure transducers are mounted on the frame. Data, power, and pneumatic lines are then interfaced to the appropriate SED-FSP components. On the deployment vessel, attachments are made to the pneumatic control mechanism, compressed air source, video monitor, and the laptop computer running the FSP-Talk data acquisition software.

5.3.2 Data Acquisition

After accessing the location and anchoring at the deployment location, the SED-FSP was lowered to the sediment surface using a crane or davit (at the Anacostia River location a davit and hand crank was sufficient to lower and raise the unit). During lowering of the system, the

on-board camera was monitored to ensure that the location was free of obstructions and the probe was correctly placed. The FSP-Talk software was then activated for data collection; then the penetration stroke was initiated by activating the pneumatic cylinder via the user operated valve control mechanism on board the deployment vessel.

During probe penetration, the video camera was monitored carefully to ensure that during probe penetration of the bottom sediments that subsurface obstructions were not encountered. If free of obstructions, a successful sediment penetration and data acquisition occurs in around 10 to 15 secs. Subsurface obstructions or excessive resistance to probe penetration are evident if the camera shows the probe to be slowing or even stop. At several of the IR Site 9 locations, the probe was stopped by sediment resistance and the drive system frame was seen to lift off the surface as the pneumatic cylinder continued to "push." When this occurred, the control valve mechanism was reversed and the probe retracted, therefore aborting the sample run. The SED-FSP assembly was redeployed at a nearby location and data acquisition was retried. At several locations at IR Site 9, data acquisition was abandoned after repeated unsuccessful tries. Continued application of stress on the SED-FSP probe risked breakage of the Delrin isolator insert, breakage of the mechanical probe/piston interface, or tipping over of the entire assembly if allowed to lift excessively.

After completion of the penetration stroke, the probe was retracted and the data acquisition and storage software was stopped. The entire data acquisition process took as little as 30 sec. The SED-FSP assembly was then raised from the sediment surface and a subsequent sampling location was acquired. Depending on ease of acquiring the new location and anchoring of the deployment vessel, the entire process could be performed in around 15 min per station.

At the IR Site 9 location, around 100 pounds of lead-shot weights were added to the drive system frame to overcome the substantial penetration resistance encountered at the near-shore locations. At locations farther out in San Diego Bay, away from the shore, the load was reduced to around 20 pounds in the softer sediments due to excessive weight causing the SED-FSP assembly to sink into the bed.

Field operations required the labor of at least four experienced personnel at the IR Site 9 location where high-energy ocean conditions were present and boat handling and SED-FSP assembly control required additional personnel. At the Anacostia River site, two experienced personnel were adequate to perform the deployment.

5.3.3 Demobilization

Demobilization of the SED-FSP and drive system consisted of cleaning, packing, and return shipping of the equipment. The demobilization phase took from ½ to 1 day depending on the number of support personnel. Decontamination of the assembly generally consisted of rinsing with site water between sites to remove any sediment residues, followed by wipe-down with a clean cloth. Decontamination at the end of the survey consisted of rinsing with site water followed by rinsing with tap water and wipe-down with a clean cloth. If high levels of contamination are encountered (e.g., dense non-aqueous phase liquid (DNAPL), heavy metals, toxics), more intensive decontamination may be required to protect personnel and avoid spreading contamination at the site.

5.3.4 Field Demonstration Schedules

The field deployment dates are shown in Table 3; they differ only in the number of days on the water, determined by the number of deployment locations. The IR Site 9 demonstration

was performed in two phases: a validation phase and a site survey phase. The validation survey supported the Environmental Security Technology Certification Program (ESTCP) demonstration program during which 27 locations were analyzed by the SED-FSP and sediment validation samples were collected and analyzed. A subsequent survey at IR Site 9 was performed in support of the broader site characterization study that is undergoing at the site (Section 4.1.1). The IR Site 9 survey targeted acquisition of 125 locations, and data was obtained from 116 locations. Survey activities were performed in 7 days between March 1, 2011, and April 19, 2011. The survey period was lengthy for several reasons: accessibility to the site was limited due to site operations, the Delrin acoustic isolator broke due to excessive stress on the probe, and the pneumatic driving cylinder broke. The survey was also delayed for several days because of substantial turbulence in San Diego Bay caused by the March 2011 Japanese tsunami.

5.3.5 Sampling Methods

Sediment sampling by divers also occurred during the demonstrations in order to obtain laboratory-verified results for comparison. The grain size analysis technique used by the contracting laboratory (ASTM, 1998) is a combined mechanical sieving and hydrometer method. The sieves are used to quantify particle sizes in the sand range (> 63 μm) and larger, and a sedimentation-hydrometer technique is used to quantify the silt and clay size ranges (< 63 μm).

Divers were used to manually collect sediment cores to ensure that the sediment sampling was collocated with the SED-FSP probe placement. At the Chollas Creek and IR Site 9 locations four replicate SED-FSP deployments and sediments were collected at three locations to quantify the effect of field variability.

5.3.6 SED-FSP Data Collection and Processing

The SED-FSP responses were recorded and stored in comma-separated values (CSV) format by the FSP-Talk software for processing. The recorded data consists of a time stamp (milliseconds) starting at the acquisition start time, the processed sound amplitude response transmitted by the electronics interface and the penetration pressure measurement transmitted by the on-board pressure transducer interface.

The SED-FSP response data were imported into an Excel template that associates output to a subsurface depth through use of the time-stamp and penetration speed. Also included in the spreadsheet template were the laboratory-determined calibration parameters for conversion of SED-FSP response to grain size. Generally, the data were examined on site to ensure that the data acquisition and collection were successful.

Table 3. Field demonstration activity schedules.

Naval Base San Diego, Chollas Creek					
Field Activities	Field Deployment Dates				
	25-Oct-10	26-Oct-10	27-Oct-10	28-Oct-10	29-Oct-10
Field/Support Vessel Mobilization					
SED-FSP and Drive System Staging					
SED-FSP Implementation/Survey					
SED-FSP Data Collection and Analysis					
Verification Sediment Sampling					
SED-FSP Demobilization					
Sample Processing and Shipment					

North Island Naval Air Station IR Site 9					
Field Activities	Field Deployment Dates				
	10-May-11	11-May-11	12-May-11	13-May-11	14-May-11
Field/Support Vessel Mobilization					
SED-FSP and Drive System Staging					
SED-FSP Implementation/Survey					
SED-FSP Data Collection and Analysis					
Verification Sediment Sampling					
SED-FSP Demobilization					
Sample Processing and Shipment					

Anacostia River Thin-Layer Cap Site					
Field Activities	Field Deployment Dates				
	13-Feb-12	14-Feb-12	15-Feb-12	16-Feb-12	17-Feb-12
Field/Support Vessel Mobilization					
SED-FSP and Drive System Staging					
SED-FSP Implementation/Survey					
SED-FSP Data Collection and Analysis					
Verification Sediment Sampling					
SED-FSP Demobilization					
Sample Processing and Shipment					

5.3.7 Sample Processing and Analysis

The sediment core samples were extruded and transferred to glass jar containers for shipment to the analytical laboratory. At the Chollas Creek and IR Site 9 locations, the sediment grain size characteristics of the surface sediments were of interest; therefore, only the top 6 in of the sediment cores were extruded and submitted for analysis to the analytical laboratory (TestAmerica Burlington Laboratory, South Burlington, Vermont).

At the thin-layer cap site on the Anacostia River, verification sampling was accomplished by analyzing selected strata within the core samples and comparing them to the associated SED-FSP responses. The project demonstration plan described obtaining six to eight sediment sections for analysis from each of the core samples, with each section projected to be collected in 2-cm lengths. Consultation with the analytical laboratory determined that a 2-cm section was an insufficient mass for the ASTM D422 grain size analysis. Laboratory estimations were made that the coarse sand or gravel that comprised the thin cap layer would provide approximately 25 g of dry mass per centimeter of sediment core. Finer materials such as silt or clay would yield around 10 g of dry mass per centimeter of core (1 7/8 in diameter). The minimum amount of mass required for PSD analysis, if characterized for the full spectrum of grain size, is around 100 g for sandy samples and 60 g for fine material (ASTM, 1998). The 2-cm sections, using laboratory estimations, would provide 50 g of sandy material or 20 g of fines material. Therefore, 2-in sections were submitted for laboratory analysis instead of the 2-cm sections that were documented in the project demonstration plan. Based on the laboratory estimates, 2 in would provide 125 g of sandy material or 50 g of fines material and also provide sufficient resolution of the vertical profile to assess SED-FSP performance. Eight cores were selected for validation and six sections per core were submitted to the contracting laboratory for verification analysis.

5.4 SAMPLING RESULTS

The validation samples collected during the three field deployments are summarized in Table 4. The table identifies the number and types of samples collected and submitted for grain size analysis by the contracting laboratory.

5.4.1 Chollas Creek, NBSD

5.4.1.1 SED-FSP Calibrations

Pre-deployment calibrations of the SED-FSP against sediments of known grain size were performed before each of the field deployments. Sediment materials of known grain sizes had been prepared by mechanical sieving to size classifications of coarse sand (0.5 to 1.0 mm), medium sand (0.25 to 0.5 mm), fine sand (0.125 to 0.25 mm), and very fine sand (0.063 to 0.125 mm). The SED-FSP responses for the known sediment classes were acquired by probing the prepared sediments in 12-in diameter x 18-in tall buckets in the laboratory. Figure 17 is the response curve for the sieved materials measured in the laboratory prior to the Chollas Creek survey; similar plots were generated for both the Anacostia River and IR Site 9 surveys. In the plots, acoustic response is plotted against the mean of the grain size, e.g., for coarse sand (0.5 to 1.0 mm), the mean value of 0.75 mm is used as the characteristic grain size. Based on the correlations from the laboratory, the linear relationships were applied in the field to the raw SED-FSP acoustical responses.

Table 4. Verification sampling summary for all deployments.

Matrix	Type	Number of Samples	Analyte	Location
NBSD Chollas Creek (Contaminated sediment site)				
Sediment	Homogenized core or grab (upper 15 cm)	23	Grain size analysis	20 SED-FSP deployment locations and 3 replicate validation stations.
NASNI Site 9 (GSI site)				
Sediment	Homogenized core or grab (upper 15 cm)	42	Grain size analysis	93 SED-FSP only stations, 27 SED-FSP deployment locations and 3 replicate validation stations.
Anacostia River Pilot Cap Study site (Thin-layer capping site)				
Sediment	Sediment core, 6 - 8 sections (2 in) per core	50	Grain size analysis	24 SED-FSP deployment locations, 8 verification sampling locations, 3 replicates at 1 location.

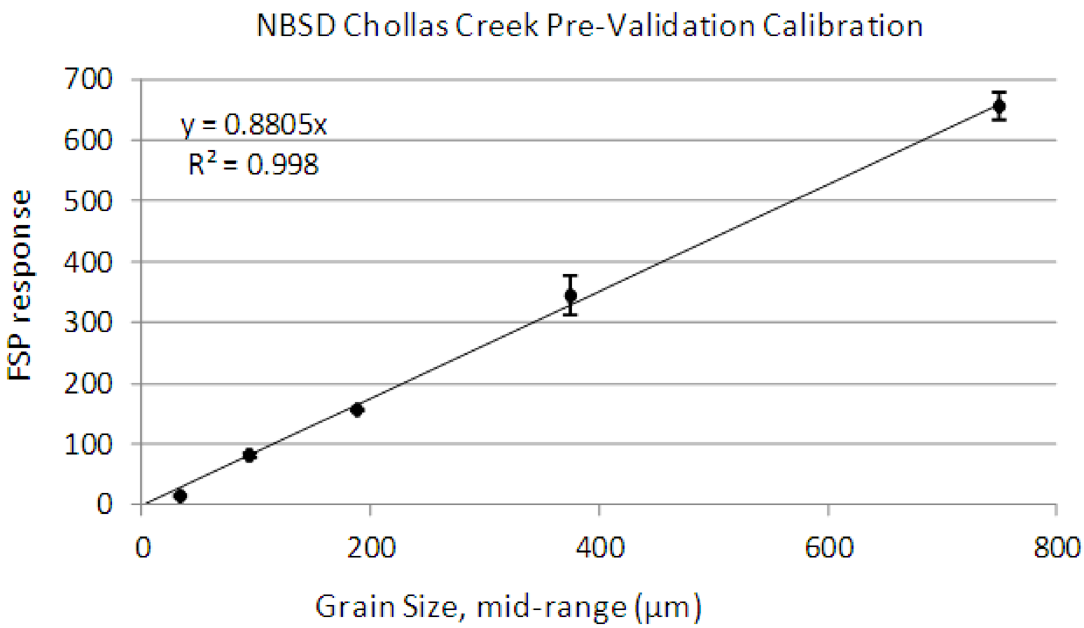

Figure 17: Laboratory calibration of SED-FSP prior to Chollas Creek demonstration deployment.

The results of the field deployment measurements are shown in Figure 18. The chart on the left is a comparison of the SED-FSP response of mean grain size as calibrated in the laboratory against mean grain size as determined by the contracting laboratory (ASTM, 1998). The data indicate that the SED-FSP unit consistently underestimated mean grain size and is not linearly correlated with the laboratory results.

The cause for the deviation from laboratory calibration is unknown but may be attributable to the calibration method. Laboratory calibration involves use of relatively small (4-gal bucket) amounts of material that are confined to a container. The SED-FSP unit was set up in the laboratory and the probe deployed into a bucket containing the known materials. The average of four acquisitions into each known sediment was used to make a calibration plot. Laboratory observations indicated that confinement in the container may impact displacement of the sediment as the probe penetrates the material, especially as the probe nears the bottom of the container. The resulting effect is that friction sound may be biased to greater amplitude. The container may also have an effect on compaction of the samples; container effects are obviously not encountered in a field application.

Use of an empirical power-law relationship to fit the SED-FSP responses to the validated grain size results gave the best fit of the data, as shown on the right side of Figure 18. Using this empirical calibration, the SED-FSP correctly classified sediments according to classifications of silt, fine sand, and medium sand, the range of sediment sizes encountered during the survey. Calibration according to a power-law fit the SED-FSP responses more accurately for all of the field deployments; its use was therefore employed for calibration of the unit.

5.4.1.2 Use of Empirical Power-Law Fit

The cause of deviation of the field responses from validated values was not ascertained during the demonstration period but is thought to in part be the result of the method of calibration. Laboratory calibration involves use of relatively small (4 gallon bucket) amounts of material that are confined to a container. For laboratory calibration of the SED-FSP system, the assembly was constructed in the laboratory and the probe deployed into a bucket containing the known materials. The average of four acquisitions into each of the known sediments was used to calculate an instrument response and calibration parameters. Observations during the procedure indicated that confinement of sediment in the container impacted displacement of sediment as the probe penetrated the material, especially as the probe neared the bottom of the container where sediment was more confined and compacted. The amplitude of friction sound increased as the probe penetrated nearer to the container bottom. The container effect was obviously not encountered in the field application.

Another possible cause of the deviation of field measurements from validated values is the nature of the calibrating sediments. The known sediments were prepared by sieving a stock material to exact size classification ranges. For example, coarse sand was sieved to the range of 500 μm to 1.0 mm with no material beyond the range limits, medium sand from 250 to 500 μm, etc. This characteristic of very well-sorted sediments is not encountered in the natural environment where sediment sizes can range broadly and distribution shape is random.

The choice to use power-law fitting was based on the resulting goodness of fit across all deployments and when globally applied to all project field data as a whole. It could not be theoretically ascertained that the measured sound amplitude and mean grain size follow a power-law distribution, but for the ranges of sizes encountered, the power-law fit was observed. Section 2 states that in the SED-FSP system friction sound is a linear function of particle size and related to the speed of the interface surfaces. It was speculated that deviations were seen because of the nature of the calibrating method and known sediments. The empirical power-law fit resulted in a SED-FSP system that could meet the project performance metrics, so it was therefore used for unit calibration.

5.4.1.3 Chollas Creek Survey Results

During October 26-28, 2010, the SED-FSP was deployed at 23 locations at the Chollas Creek site. Generally, each deployment required separate anchoring, and sediment cores were collected by divers at each of the deployment locations. The survey was the first use of the technology in a field environment. Technology-use issues encountered for the first time included arriving at a correct and consistent sequence of video capture, data acquisition, pneumatic source activation, and general use of the instrument. Resistance of the sediment bed to probe penetration was an unanticipated occurrence encountered for the first time and required resolution in the field. Though the first use of the technology in a field environment presented issues that had not been encountered or addressed previously, the rapidity and ease of using the technology was demonstrated. After navigating to and securing position at the sampling station, it was found that lowering of the SED-FSP, acquiring the acoustic responses, then raising of the unit could be achieved in under 5 min. Migrating the data to a Microsoft Excel® spreadsheet template was accomplished in under 1 min. The processed data resulted in acquisition of a grain size, on the surface and at depth, in minutes.

A contour map of grain size of the surface sediments was generated (Figure 19) by averaging the SED-FSP responses corresponding to the upper 6 in of sediments. The mouth

of the creek, as it encounters San Diego Bay, appears to be dominated by larger particles, mainly as a result of measurements obtained at locations C18 and C11. The rest of the area is dominated by sediment in the fines size range.

In contrast, the map generated during the previous TMDL study (Figure 15) appears to show greater variety of sizes when compared. Note that in the TMDL study, the results are presented as a map of percent fines (10% intervals), whereas in the SED-FSP survey, the resulting size classifications (coarse sand, medium sand, etc.) are plotted. The TMDL study results showed that the grain sizes at the extreme mouth of the creek were of larger size (10.9% fines at C08) and decrease in size substantially away from the mouth (e.g., 62% fines at C03). Generally, the results corroborate the SED-FSP results that identified larger grain sizes at the mouth.

A discrepancy in the comparison is found on the northern section of the Chollas Creek mouth. Referring to Table 2 (TMDL study) 90% sand was encountered at stations C07 (see Figure 15) while at this site the SED-FSP measured silt. The validation grain size analysis performed by the contracting laboratory showed percent fines of 75% at this location. At C16, the adjoining location, fines of 68% were measured. The validation analysis performed by the contracting laboratory confirmed the SED-FSP measurement.

5.4.2 Naval Air Station North Island – IR Site 9

5.4.2.1 SED-FSP Calibrations

The NASNI IR Site 9 survey results were similarly processed as the Chollas Creek data and the resulting grain size measurements compared to the laboratory-validated results. The pre-deployment calibrated SED-FSP measurements and the power-law, curve-fitted data are shown in Figure 20. Like the Chollas Creek demonstration results, the laboratory-calibrated SED-FSP consistently underestimated the contracting laboratory-analyzed grain sizes, but could correctly classify the sample sediments when a power fit was applied, with several exceptions.

Certain of the SED-FSP measurements taken near shore at IR Site 9 consistently over-estimated grain sizes compared to the laboratory measured values and are not correlated with the remaining data. These data are circled in the left-side plot of Figure 20 in the fine-sand size range. Review of the survey notes indicated that these station locations were acquired at low tide when the stations were not submerged, i.e., on the beach. The SED-FSP assembly had not been lowered from the deployment vessel but had been hand-carried to the shore locations. The measurement error was attributed to probing into a dry sample matrix. All previous work with the SED-FSP was in water-saturated sediments, there is no experience or characterization of the SED-FSP with dry sediment or soil applications. These data points were excluded from analysis of the results and further reporting.

5.4.2.2 IR Site 9 Survey Results

The deployment locations at the IR Site 9 location were along a series of 12 offshore transects that encompass the groundwater discharge zone identified in previous studies (SPAWAR, 2001). Figure 21 shows the 116 deployment locations that were successfully acquired during the field effort. Also included in the figure are the historical sampling locations (red symbols with “PW” labels) that indicated evidence of contaminated ground-water seepage into San Diego Bay. Validation sampling by divers was performed on transects 3, 5, 7, and 9 in a separate survey. At three of the stations, field replicate SED-FSP responses and sediment core samples were collected to quantify field variability. At several near-shore

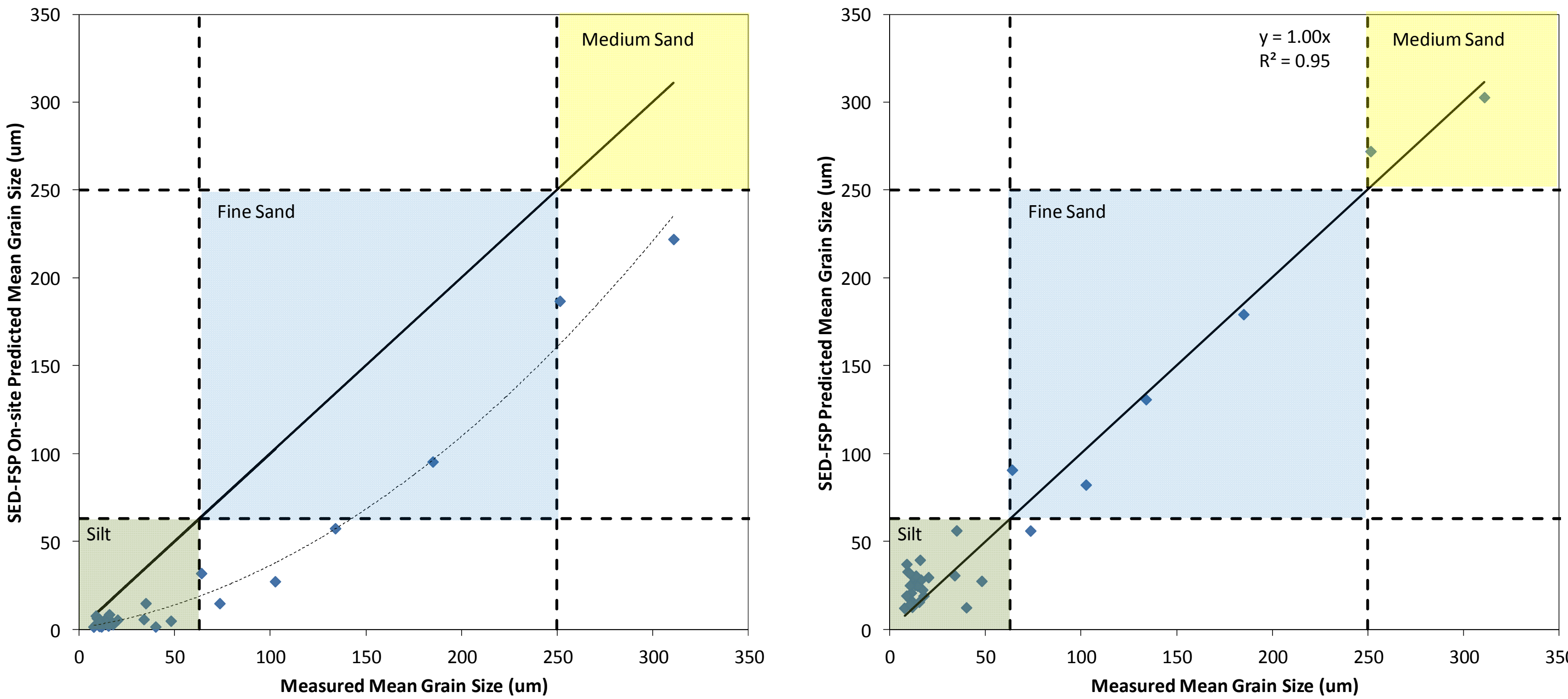

Figure 18. SED-FSP results for Chollas Creek validation survey showing linear (left) and power-law calibration of the unit (right). The dashed line in the left-side plot indicates the data trend and is not a fit of the data.

Figure 19. SED-FSP survey results for mouth of Chollas Creek at NBSD.

locations, resistance to penetration caused the deployment to be abandoned without further probing at that location. At the third location on transect 7, the penetration force applied to the probe was great enough to break the Delrin probe insert. The survey was postponed for several days until the insert and microphone could be replaced. Subsequent deployments near shore were not as aggressively pursued.

Unlike the Chollas Creek deployment, the vertical profiling capabilities of the SED-FSP were used to further characterize the site (Figure 22 and Figure 23). The contour maps created are of four subsurface depth intervals providing a site-wide representation of the SED-FSP size classifications as a function of subsurface depth. The patterns are useful in understanding potential groundwater discharge pathways, especially as the groundwater approaches the shallow sediment zone (within 2 ft of the interface).

Based on the sediment texture maps, several patterns and trends are evident. First, a pattern of coarser grained materials is near the shoreline, progressing offshore to finer materials near the pier finger extending toward the south, transitioning to somewhat coarser material further offshore from the pier. Also, there is a general trend towards coarser materials at depth across the site. Finally, stations where VOCs were detected in the shallow subsurface (~ 1-ft depth; SPAWAR, 2001) tend to reside at the inshore boundary between the coarser shoreline materials and the finer offshore materials. Stations where VOCs were detected previously only at the deeper horizon (~ 3-ft depth) tend to align with the coarser materials offshore or at depth. Together, these results suggest that fine grain materials near the pier may be acting to retard the discharge of VOCs in the pier area, and discharge is directed more to the zone inshore of these fine-grained materials or perhaps beneath the fine layer into coarser sediment offshore of the pier.

5.4.3 Anacostia River Active Capping Pilot Study Site, Washington, D.C.

5.4.3.1 SED-FSP Calibrations

Similar to the Chollas Creek and IR Site 9 field efforts, Figure 24 was constructed to show comparisons of the linearly calibrated SED-FSP (left) and power-law calibrated unit (right) responses to validated grain sizes. Coarse sand material is a major constituent of the sand cap material and was anticipated for this site; this was observed in the sample sediments and evident in the laboratory analyses where very coarse sand (1 to 2 mm) and gravel (2 to 4 mm) was encountered in nearly all of the containment cap samples. The Figure 24 chart shows greater dispersion around the regression curves and appears significantly more linear in comparison to the previous two field efforts and under-predicts the grain size but to a lesser degree than the other deployments.

Data outliers encountered during the field survey are identified as circled data in the left-side plot. Review of these particular locations show that two of these data points correspond to the interface of the capping material and the underlying native sediment. In one case, the SED-FSP substantially under-estimated the laboratory validated grain size; for the other point. the opposite is the case. The cause of these outliers is attributed to sampling artifacts related to the abrupt change of sediment type at the interface from coarse sand to silt; an error in assignment of vertical depth could account for a substantial error, either in over-estimating or under-estimating size. These two data points were excluded from further characterization and analysis while the third outlier, not at the cap interface, was retained.

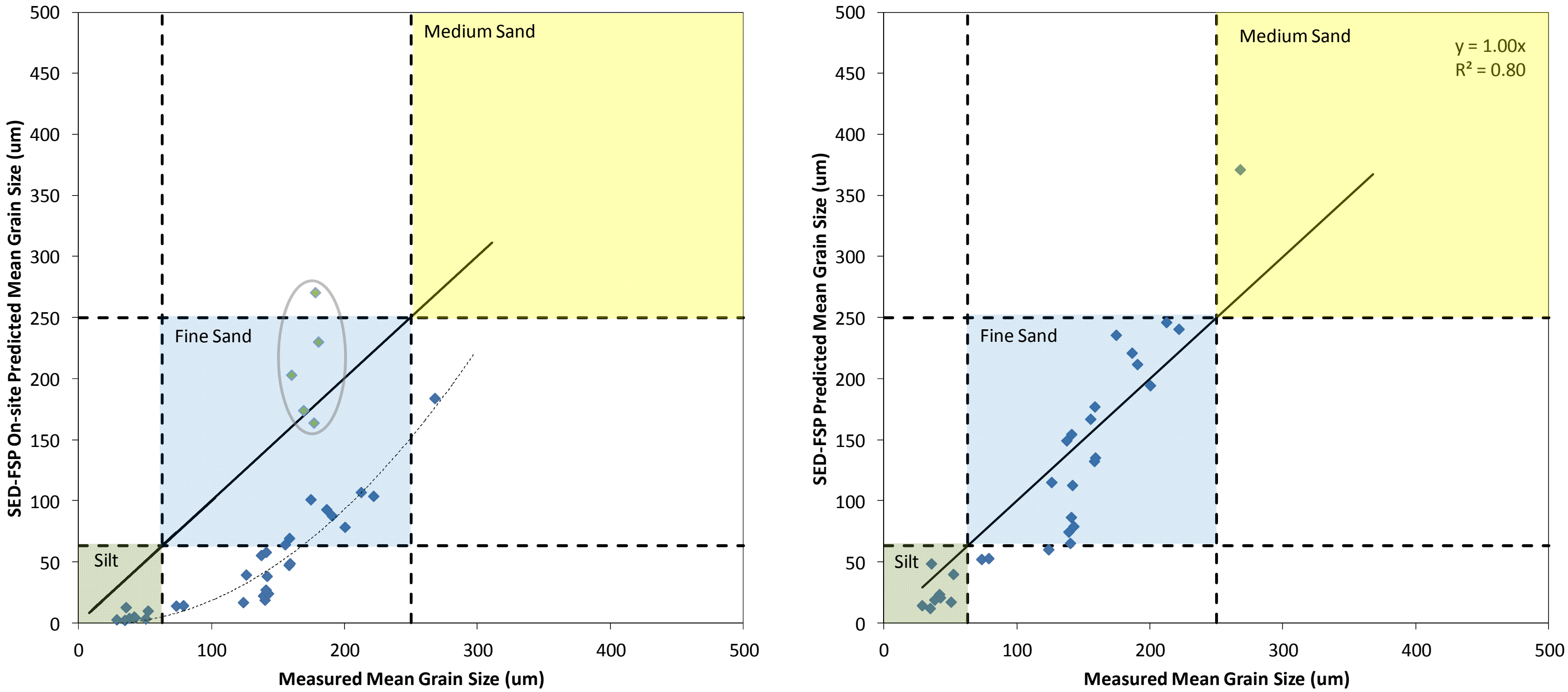

Figure 20. SED-FSP results for IR Site 9 validation survey showing linear (left) and power-law fit (right) including data (left) that is excluded from calculations. The dashed line in the left-side plot indicates the data trend and is not a fit of the data.

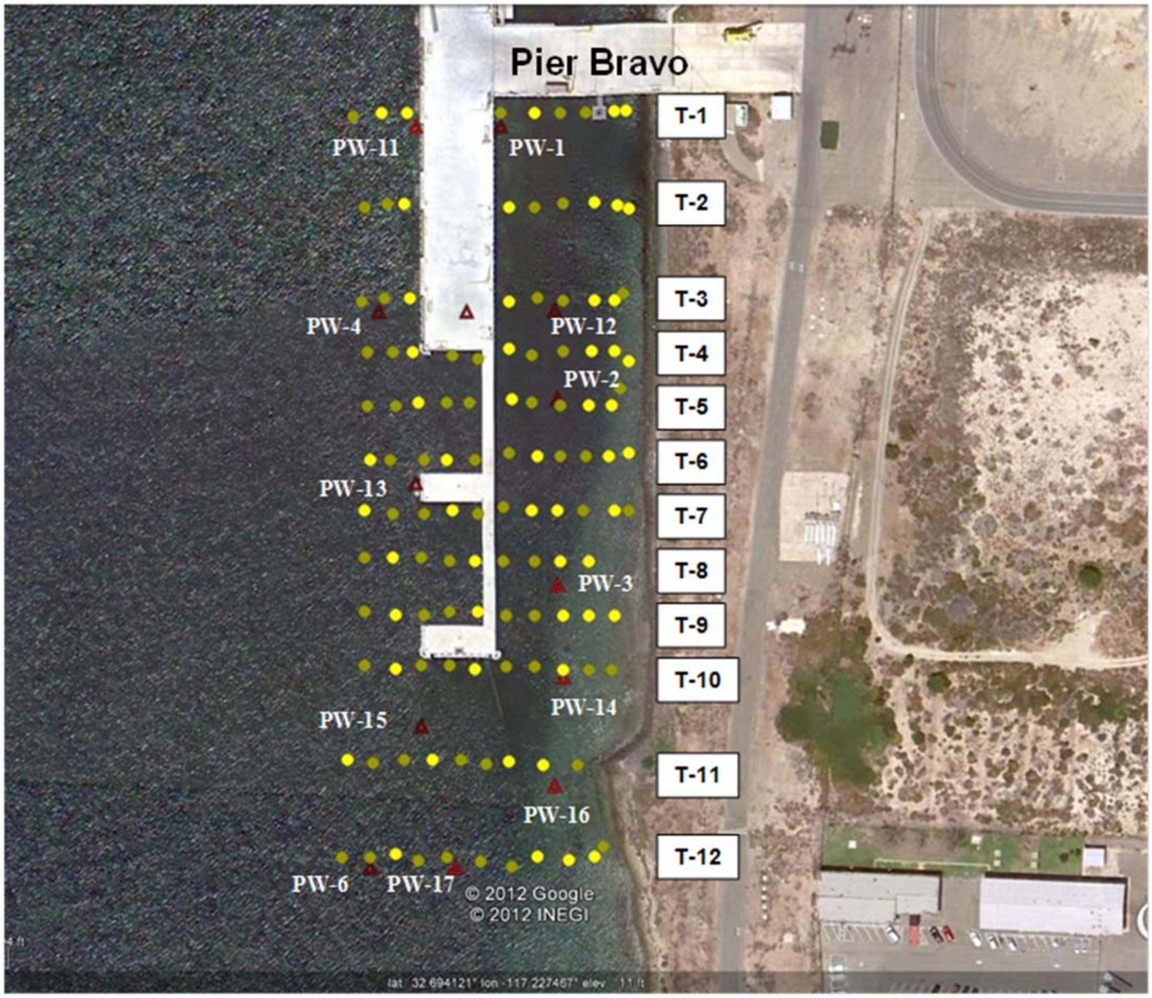

Figure 21. IR Site 9 SED-FSP deployment locations, including transect identifications and historical porewater sampling locations (red symbols with "PW" labels).

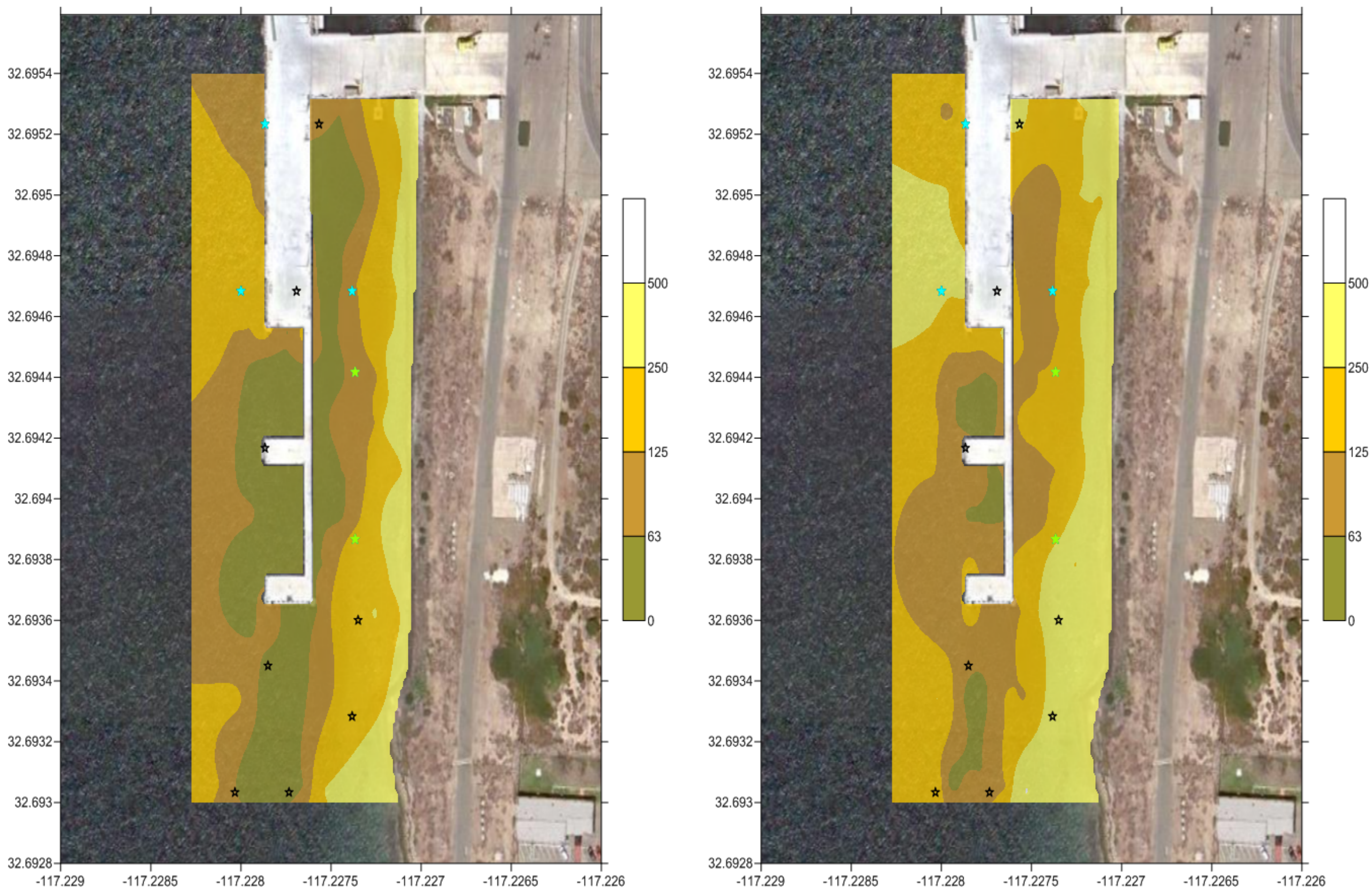

Figure 22. SED-FSP estimated mean particle size map for the 0- to 6-in (left) and 6- to 12-in (right) depth intervals. Black outlined stars indicate historical sampling locations where no VOCs were detected. Blue stars indicate historical sampling locations where VOCs were detected in deep samples (~ 5 ft), and blue stars indicated historical sampling locations where VOCs were detected in both shallow and deep samples (~ 1 ft and ~ 5 ft).

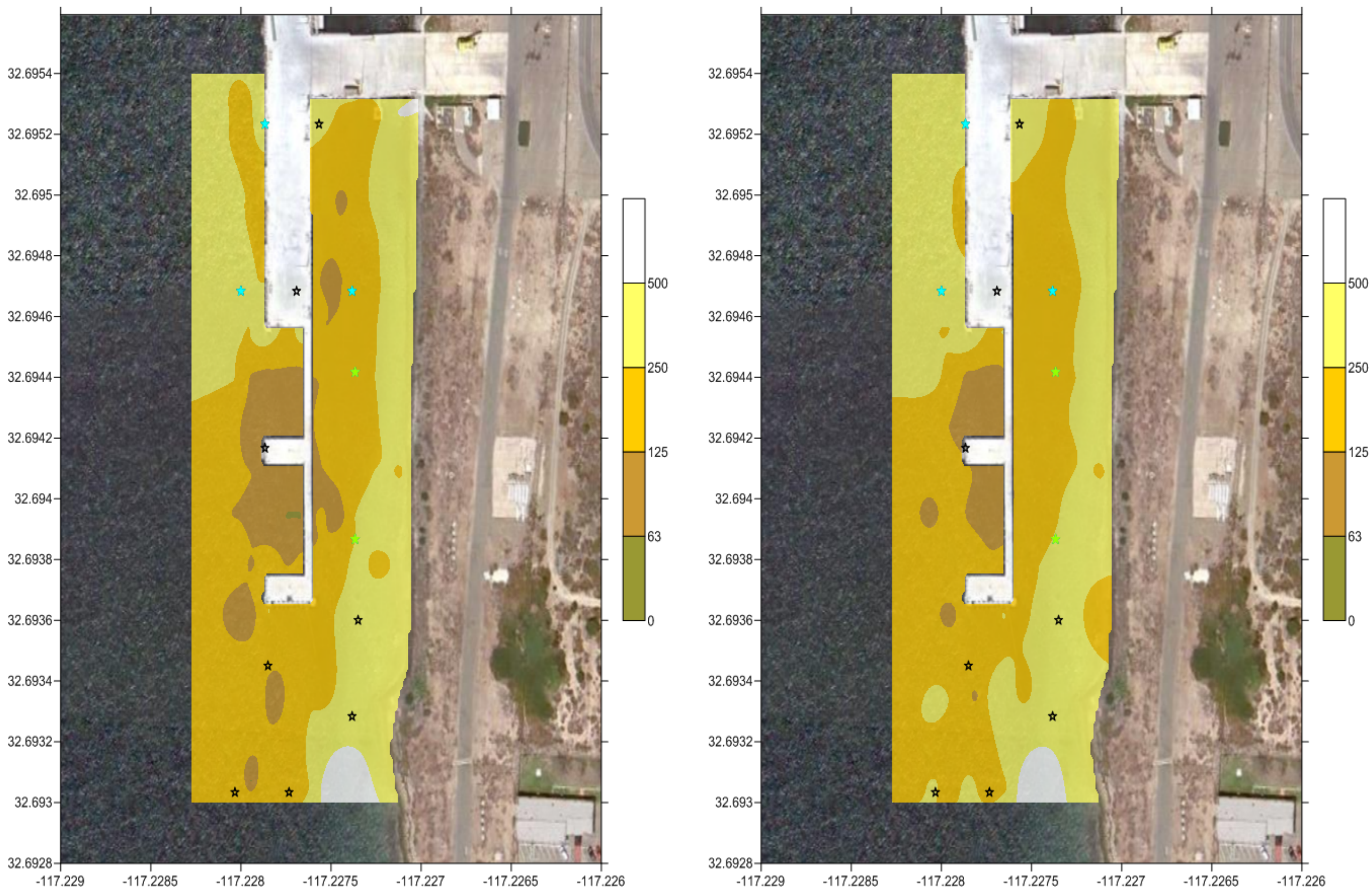

Figure 23. SED-FSP estimated mean particle size map for the 12- to 18-in (left) and 18- to 24-in (right) depth intervals. Black outlined stars indicate historical sampling locations where no VOCs were det ected. Blue stars indicated historical sampling locations where VOCs were detected in deep samples (~5 ft), and blue stars indicated historical sampling locations where VOCs were detected in both shallow and deep samples (~ 1 ft and ~5 ft)

5.4.3.2 Anacostia River Thin-Layer Cap Survey Results

The vertical profiling capability of the SED-FSP system was demonstrated at the sand cap study site. The sand cap was constructed in March 2004 as part of a study characterizing the efficacy of active cap technologies (see Section 4.1.3). According to the study site placement plan, the target thickness of the sand cap was 12 in. A post-placement study conducted soon after installation found the actual average thickness to be 8.9 ±3.2 in, ranging from 0.25 ft at the edges to 1.25 ft at the southeastern corner (Ocean Surveys, 2004). Though the AquaBlok portion of the characterization study continued for 30 months until 2006, the last sand cap cell assessment was made 6 months after placement in September 2004.

Attempts were made to acquire sand cap thicknesses that were acquired during subsequent work at the site from the project general contractor (Horne Engineering Inc.) during the 2004 deployment but these were not obtainable. Note that the SED-FSP sampling plan did not attempt to reacquire core sampling locations that had been acquired in the previous studies. The basis for selecting the sampling locations was to fully cover the sand cap location and verify the presence of the cap material and its depth.

In Figure 25, the yellow polygon represents the sand cap location based on data reported by the placement contractor (Horne Engineering Services, Inc., 2004). Also included in the figure are the target sampling locations and their field identifications. The locations were selected to provide full and even coverage of the demonstration site including locations on the adjacent native (uncapped) sediments. The field effort consisted of three transects over the cap in a northeastern to southwestern direction with the transects approximately 25 ft apart. Eight locations per transect were selected, four locations on the cap and two locations each on the north and south ends of the cap. Therefore, 12 deployments were made on the cap and 12 were made off of the cap (Figure 25). Sediment cores were collected at 11 of the 12 cap locations (seven were submitted for validation analysis) and two sediment cores were collected off the cap (one was submitted for validation analysis). The SED-FSP and verification sampling results confirmed that the cap location provided by the placement contractor was accurate.

The cap was small enough in size that a three-point anchor setup could be used with only two adjustments during the deployment. An 8-ft by 12-ft pontoon platform, shipped from SSC Pacific in San Diego to the location, was used as the deployment platform with support of a locally rented bass fishing boat for transiting from the launch location (Joint Base Anacostia-Bolling) to the Anacostia River deployment site (Figure 26).

Cap thickness was determined by selecting a threshold value of SED-FSP response that would indicate the interface of the cap material and underlying native sediment. Evaluation of the vertical profiles generated from the SED-FSP responses showed that the acoustic intensity of friction sound generated by the top layer cap material was accurately measured by the SED-FSP. The SED-FSP response to the native sediment underlying the cap material was substantially greater than what would be estimated for the native fines that constituted the underlying sediments. The native sediment was measured by the analytical laboratory in the silt to very fine sand range. The high SED-FSP response to the underlying layer is attributed to insufficient acoustic isolation of the probe tip from the rest of the probe shaft. As the probe tip breaks through the cap material into the underlying finer sediments, the probe shaft continues to generate considerable friction sound along its 1-m length that is picked up by the microphone sensor at the tip. This is true in spite of the Delrin isolator that is positioned near the probe tip. However, the upper cap/underlying sediment interface is

positioned near the probe tip. However, the upper cap/underlying sediment interface is clearly identifiable when visually examining the profile data. Determination of the location of the cap-sediment interface was made by selecting a threshold value indicating the interface. The selection was based on observations of SED-FSP responses and core samples along the middle transect (locations AR-11, AR-12, AR-13, and AR-14), the value selected is approximately at the mid-point between the responses to cap material and underlying sediment. The method may be modified if this particular application is encountered again or further efforts to isolate the acoustic response along the probe shaft may be incorporated into the SED-FSP system.

The survey results are shown in Figure 27 with the colors of the symbols indicating depth horizons of the capping material as measured by the SED-FSP. The tables show that the cap is greatest in thickness in the eastern corner and generally less on the southwestern portion (Figure 27). At locations AR-07 and AR-15, cap thickness was measured in the 1- to 5-in interval; these locations are off the cap target area. Larger particles were not measured at any of the off-cap locations.

The average cap thickness, based on the 12 on-cap deployment locations is 14.3 ±4.2 in, within limits of the target thickness of 12 in and the thickness of 8.9 ±3.2 in measured by the placement contractor. The photo of a site core is provided in Figure 28, clearly showing cap material from 4 to 18 in, or ~ 14 in thickness.

5.4.4 Global Application of Calibration Parameters

All SED-FSP responses that were validated by laboratory analysis have been fitted to the data and are accumulated in Figure 29. Calibration of the SED-FSP unit is a two-step process; pre-calibration in the laboratory uses prepared sediments of known sizes and post-deployment calibration using site sediments. Pre-calibration of the unit before deployments is required due to possible changes to SED-FSP responses because of replacement or repositioning of the microphone sensor or the Delrin insulator. The results for the laboratory-calibrated SED-FSP across the three application regimes were then combined and an empirically derived power-fit applied to all the data. Those results are shown below. The global power-fit relationship was used to calculate the performance criteria discussed in this report. The global relationship applied to all the data is

$$\textit{Mean Grain Size} = 6.114 \times (\textit{Calibrated-FSP})^{0.861}.$$

The consistency of the data across these three demonstrations indicates that this global, empirical calibration may be applicable at other sites at similar levels of reliability, efficiency, and specificity as described here. The relationship will continue to be adjusted as necessary and evaluated for subsequent deployments.

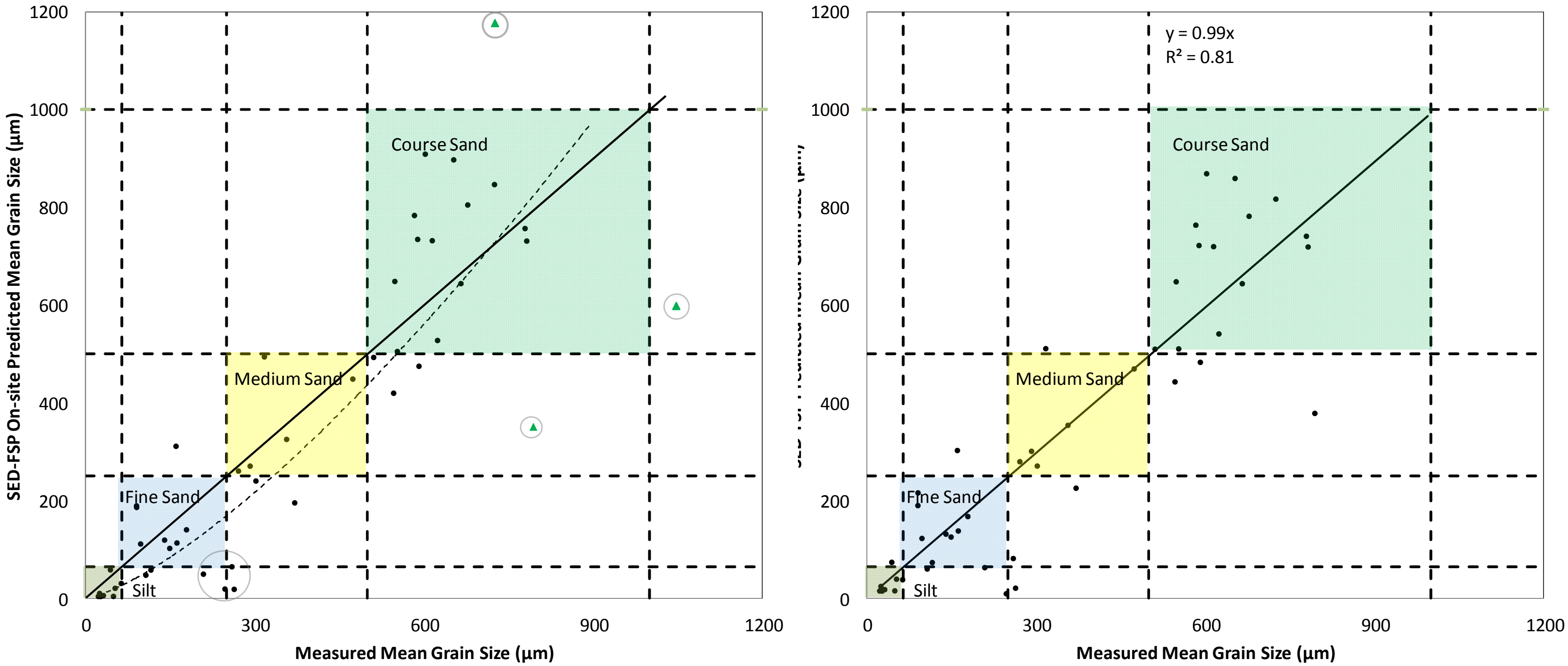

Figure 24. SED-FSP results for Anacostia River IR Site 9 validation survey showing linear (left) and power-law fit (right side). The dashed line in the left-side plot indicates the data trend and is not a fit of the data.

Figure 25. Anacostia River thin-layer sand cap site identifying the cap placement (yellow/green polygon) and SED-FSP deployment locations (orange symbols).

Figure 26. Pontoon platform with SED-FSP system assembly and locally rented support boat.

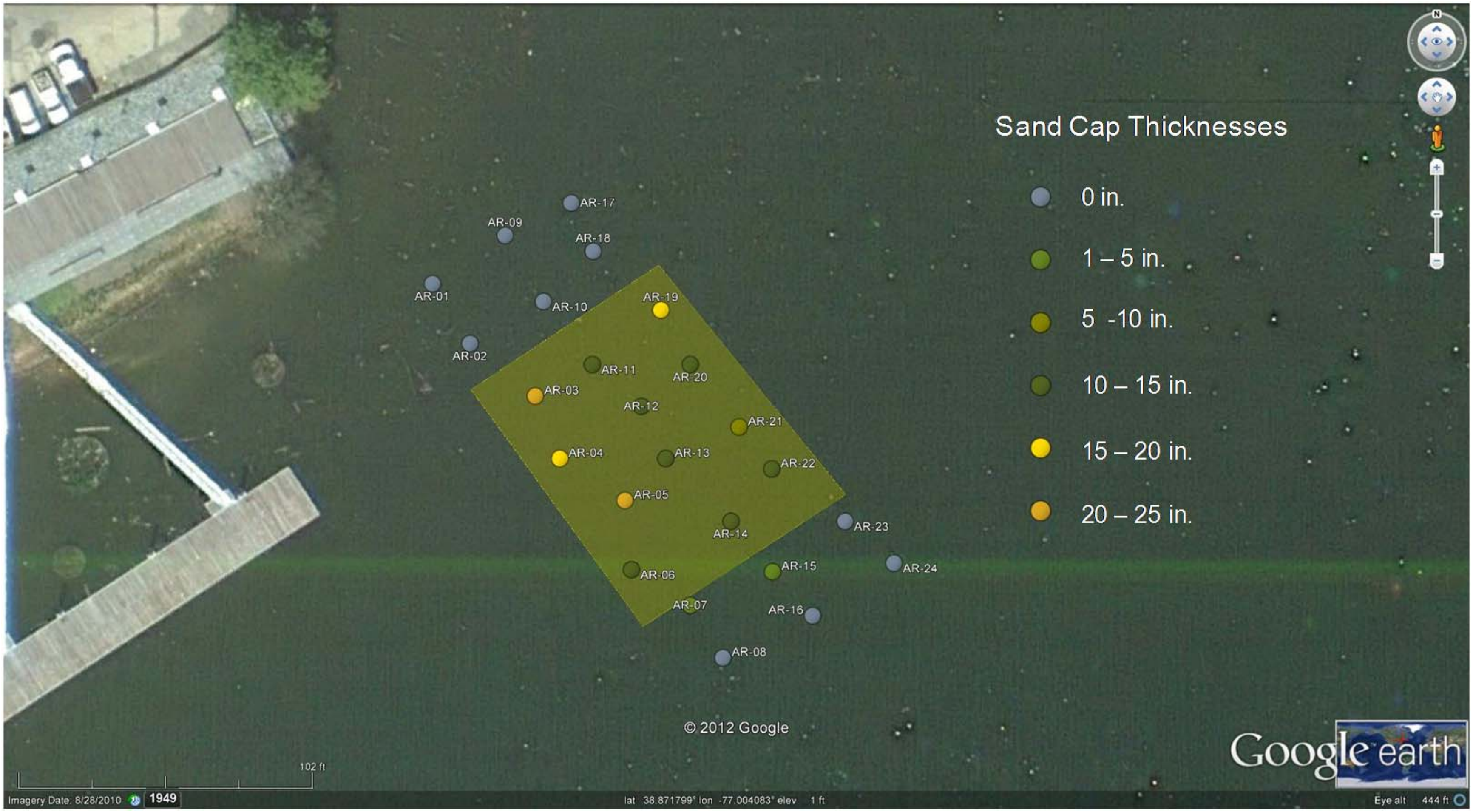

Figure 27. SED-FSP grain size survey results for Anacostia River sand cap field deployment. Rectangular area is cap location according to the placement contractor. Symbols represent depth horizons of cap material as measured by the SED-FSP system; the legend on the right side of the figure indicates the depth of cap material.

Figure 28. Sediment core sample collected during sand cap survey.

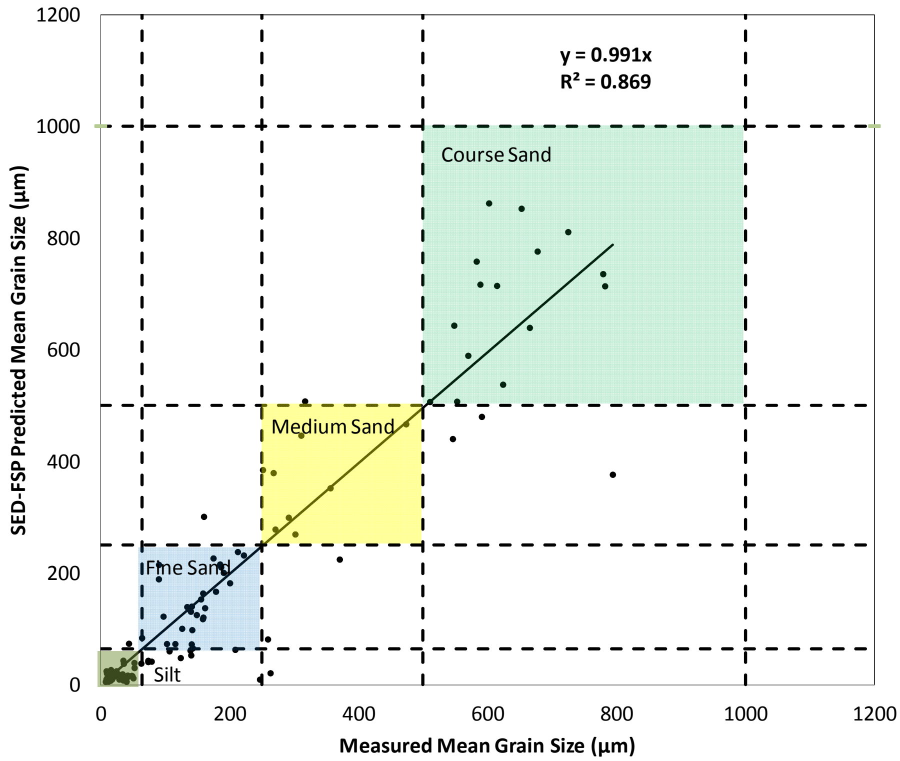

Figure 29. Global SED-FSP calibration - Chollas Creek, IR Site 9, and Anacostia River thin-layer cap deployments.

6. PERFORMANCE ASSESSMENT

The project performance objectives were met. The objectives focused on rapid, in situ classification of surface sediment type (quantitative) over a broad range of applications and conditions (qualitative). The quantitative objective was achieved by meeting the stated criteria for the objectives of reliability, efficiency, and specificity by corroboration of SED-FSP results with verification analysis of sediments. The qualitative performance assessment was achieved by providing rapid in situ survey maps delineating areas of significance at the three application regimes.

6.1 PERFORMANCE OBJECTIVES

6.1.1 Objective 1: Rapidly Classify Surface Substrate In Situ

Success was based on meeting criteria to accurately and rapidly measure sediments in situ. The success criteria were defined as follows:

- Reliability – Measure of the percentage of correctly classified stations in comparison to the total number of stations
- Efficiency - For each grain size classification (sand, silt, clay), efficiency measures the percentage of correctly classified stations in that level in relation to the total number of stations classified in that level
- Specificity - Measures percent of correctly classified stations in that level out of the total number of stations actually in that level

The target goals for reliability, efficiency, and specificity were set at 80%. The summary of the criteria results are shown in Table 5. Efficiency and reliability are determined for sand and silt grain size classes separately while the reliability criteria is based on all size classifications. Neither the laboratory-analyzed samples nor the SED-FSP responses yielded clay-sized classifications; therefore, efficiency and specificity criteria are not reported for clay.

6.1.2 Objective 2: Demonstrate Applicability for a Range of Applications

Confirmation for this objective was achieved by meeting the stated criteria for rapidly providing survey maps delineating areas of significance at the three application regimes: (1) a GSI site, (2) a contaminated sediment site, and (3) a thin-layer cap. Investigators confirmed this objective through analytical validation, review, comparison to historical studies, and best professional judgment. The objective was demonstrated by the ability to perform the following:

- Mobilize, operate, and demobilize the equipment
- Rapidly operate the system in situ
- Produce spatial maps of surface and sub-surface grain size
- Identify potential groundwater discharge zones, areas of high fines associated with contaminated sediments, and extent and depth of a thin-layer sand cap

Table 5: Performance criteria surpassed goals for reliability, efficiency, and specificity. The table shows number of stations and result percentages.

<table>
<tr><th rowspan="2">Target Criteria</th><th colspan="5">Measured Criteria</th></tr>
<tr><th colspan="3">Description</th><th>No. Stations</th><th>Result</th></tr>
<tr><td rowspan="2">Reliability - 80%</td><td colspan="2" rowspan="2">Reliability</td><td>Correctly predicted stations.</td><td>103</td><td rowspan="2">92%</td></tr>
<tr><td>Total stations.</td><td>112</td></tr>
<tr><td rowspan="4">Efficiency - 80%</td><td rowspan="4">Efficiency</td><td rowspan="2">Silt</td><td>Correctly predicted silt stations.</td><td>39</td><td rowspan="2">85%</td></tr>
<tr><td>Total predicted silt stations.</td><td>46</td></tr>
<tr><td rowspan="2">Sand</td><td>Correctly predicted sand stations.</td><td>64</td><td rowspan="2">97%</td></tr>
<tr><td>Total predicted sand stations.</td><td>66</td></tr>
<tr><td rowspan="4">Specificity - 80%</td><td rowspan="4">Specificity</td><td rowspan="2">Silt</td><td>Correctly predicted silt stations.</td><td>39</td><td rowspan="2">95%</td></tr>
<tr><td>Total silt stations. (ASTM)</td><td>41</td></tr>
<tr><td rowspan="2">Sand</td><td>Correctly predicted sand stations.</td><td>64</td><td rowspan="2">90%</td></tr>
<tr><td>Total sand stations. (ASTM)</td><td>71</td></tr>
</table>

7. COST ASSESSMENT

7.1 COST REPORTING

Evaluation and acceptance of the SED-FSP technology is partly based on demonstrating that the technology offers cost savings relative to obtaining comparable results by traditional or other methods or surveys. Evaluating or applying a metric to the ease of use and rapidity of obtaining results and generating a site characterization map is less obvious and cannot be quantified. Because the system and its components and implementation are non-complex, calculating costs for making comparisons is straightforward. Navigational and equipment handling costs associated with deploying the SED-FSP technology are similar to the deploy-ment of grab or core samplers or other field collection techniques. The difference in the technology comparison therefore lies in the method of obtaining the grain size measurement. In the case of the SED-FSP, the probe is activated on the sediment bottom and data is acquired then processed and analyzed. In the case of traditional methods, a sample collection device (grab, core sampler) is deployed on the sediment bed, the sample is raised to the surface and extracted from the device, the sample is handled (sample container, labels, documentation, custodial management, storage, etc.), the sample is processed (homogenized, extruded), shipped, analyzed (ASTM D422, textural analysis, instrumental method), and reported.

7.2 COST ANALYSIS

7.2.1 Cost Basis

The cost basis for analysis can be taken directly from the demonstration field efforts. The field efforts were real applications of the technology, in the case of the IR Site 9 survey the SED-FSP effort was integrated into a comprehensive feasibility study work plan scheduled for Spring 2015 (NAVFAC SW, 2009). The Chollas Creek demonstration was similar in spatial scope, and of higher resolution, than a previous site characterization study. Scale-up in costs would be directly related to the spatial scale and sampling resolution of future applications.

7.2.2 Cost Drivers

The key cost drivers for application of the SED-FSP system are capital costs, labor, transportation, and those associated with planning, mobilization, demobilization, data analysis, and reporting. Capital costs can be easily recaptured based on savings over traditional methods of acquiring grain size surveys of comparable scope and resolution.
As field personnel gain knowledge and experience in using the system and other site characterization tools are leveraged (e.g., Trident, UltraSeep), personnel will become more efficient or be available at lower labor rates to execute the project.

The main operating costs are associated with the labor costs and number of personnel required for navigation and equipment handling; this ranged widely for the three demonstra-tions. These were mainly determined by the effort required to navigate to and acquire the station and maintain the location. At IR Site 9 at the mouth of the channel to San Diego Bay, ocean conditions were present, requiring that a crew of at least four experienced boat handlers to operate the deployment vessel (not including the SED-FSP operator). On the other hand, at the slow-moving, low-energy Anacostia location, only a single boat operator and a SED-FSP operator were required to complete the task (Figure 26). As stated earlier, the boat-handling capabilities are similar whether the SED-FSP is deployed or samples are collected for analysis. Other factors included processing and analyzing data and writing field, survey, and final reports.

System maintenance is minimal because the system is non-complex, but failure or breakage of components needs to be addressed. Replacement parts would be required from the manufacturer, and costs would be recouped as savings over the use of traditional grain size survey methods.

7.2.3 Life-Cycle Costs

Estimates of life-cycle costs were based on the expected working life of the systems (5 to 10 years). The current rates indicate that the capital investment for the SED-FSP, including ancillary equipment, could be recouped within the expected 5- to 10-year working life, with ~ 30 uses a a year, which is well within the expected market demand for the technology (Table 6).

Table 6. Rental rates for the SED-FSP based on life-cycle costs.

Estimate of Initial Cost for Capital and Ancillary Equipment			
Item			Initial Cost
SED-FSP			$ 5,000
Ancillary - Air Compressor/Supply			$ 500
Ancillary - Field Computer			$ 500
Ancillary - Drive System			$ 4,000
Total SED-FSP			$ 10,000
Equipment Replacement Cost Estimate			
Inflation Rate	*4%*		
	Years of Use		
	0	5	10
SED-FSP & Ancillary Replacement	$ 10,000	$ 12,000	$ 14,000
Estimated Rental Rate Including Inflation and Maintenance			
Maintenance Rate	*5%*		
		Years of use	
	Uses/year	5	10
SED-FSP & Ancillary	10	$ 252	$ 147
	20	$ 126	$ 74
	30	$ 84	$ 49
	40	$ 63	$ 37
	50	$ 50	$ 29
Estimated Rental Rates (per/day)			
SED-FSP			$ 50
Ancillary - Air Compressor/Supply			$ 25
Ancillary - Field Computer			$ 25
Ancillary - Drive System			$ 50
Total SED-FSP			**$ 150**

7.3 COST COMPARISON

The cost comparison for a hypothetical grain size survey using the SED-FSP technology and a survey based on sample collection and grain size determination by traditional and other methods is described in Table 7. Excluded in the costs are travel, shipping, and boat and crew costs. It is assumed that these would be similar for SED-FSP and field efforts using traditional sampling equipment (e.g., a sediment corer). The SED-FSP footprint and weight is similar to standard sampling devices; therefore, boat- and equipment-handling requirements would be similar. The surveys in Table 7 are for two days for acquisition of 32 stations. The estimates assume that a single station is acquired every 30 min in an 8-hr day for both the SED-FSP and the sediment sampling method. In the case of the SED-FSP, this is a conserva-tive estimate. During actual usage, the on-station duration was often as short as 10 min, but averaged 15 to 20 min, even with collection of

validation samples by a diver. For a traditional sediment sampler, 30 min per sample may be an underestimate of the time required. Based on actual experience, a sediment sampler requires recovering the sampler to the deck of the vessel (not necessary with the SED-FSP), unloading of the sediment sample, possible decon-tamination steps, loading of the sampler with containers, and on-board processing (core extrusion, mixing, etc.).

The SED-FSP survey estimate also includes sample collection at 25% of the total stations for collection of site validation samples. The 25% estimate was based on the validation sampling performed during the demonstration field efforts. At Chollas Creek, 100% of the stations were sampled for validation; at IR Site 9, 23% of stations were sampled; and at the Anacostia River location, 25% of the stations were sampled. The need for and the number of samples required for site-specific validation is important because it can substantially increase costs as is evidenced in Table 7. As the technology and its use matures and/or techniques are developed and acquired that address calibration of the unit, the need for site-specific and validation samples may be reduced or even eliminated.

The labor costs for SED-FSP operation and deployment of traditional sampling equipment are nearly the same, $11,280 for SED-FSP compared to $11,050 for sampling. The differences in the non-labor costs are substantial, due primarily to differences in the number of samples submitted for validation analysis. In the bottom part of Table 7 ("Analytical" section), costs are presented for four other methods of grain size analysis: traditional sieving and sedimentation (ASTM, 1998), laser diffraction, electro-zone sensing, and microscopy. The number of samples submitted for analysis by traditional (or other) methods are 32 and the number submitted for SED-FSP validation are 8. This difference substantially influences the overall project costs (bottom of Table 7).

A simplified sieving technique that determines size texture (e.g., 2-mm and 63-µm sieves) was also considered that would represent the most rudimentary technique of grain size analysis. But the effort is non-trivial; hardware preparation is required, sieving is time consuming as would be sample handling and drying of samples, and documentation is required at each step. The cost estimate of the ASTM D422 method closely represents the cost of a basic sieving technique.

Table 8 is a comparison of project costs, excluding the analytical costs associated with site-specific calibration of the SED-FSP. The table reveals that validation sampling and analysis adds substantially to the overall costs of a SED-FSP deployment. Substantial cost advantages would be gained by reducing or eliminating this requirement. This may be accomplished as the technology matures and experience is gained through its continued use.

Not addressed in the cost evaluation is that the hypothetical survey represents a surface-characterization study only, not capturing the effectiveness of the technology for acquiring a three-dimensional survey map. Adjusting to account for the vertical dimension, accomplished by coring and sectioning, would result in substantial increases in analytical costs.

Table 7. Cost comparison of a survey for grain size using SED-FSP system and traditional sediment sample collection and analysis by standard method.

Cost Category	**Description**	**SED-FSP**			**Alternate (inc./sampling)**			
Labor Cost		Rate	Hours	Cost	Rate	Hours	Cost	
Mobilization	Calibration	$ 120	6	$ 720	$ 120	0	$ -	
	Checks/Preparation	$ 120	8	$ 960	$ 120	8	$ 960	
	Packing	$ 65	4	$ 260	$ 65	8	$ 520	
	Shipping	$ 65	2	$ 130	$ 65	2	$ 130	
Sub-total				$ 2,070			$ 1,610	
SED-FSP Operation	On-site Setup/Testing	$ 120	4	$ 480	$ 120	0	$ -	
	Equipment Handling	$ 65	16	$ 1,040	$ 65	0	$ -	
	Operator/User	$ 120	16	$ 1,920	$ 120	0	$ -	
	Data Processing	$ 120	4	$ 480	$ 120	0	$ -	
Sub-total				$ 3,920			$ -	
Sediment Sampler Operation	On-site setup/Testing	$ 120	4	$ 480	$ 120	4	$ 480	SED-FSP sediment validation costs for sample collection at 25% of total locations.
	Equipment Handling	$ 65	6	$ 390	$ 65	24	$ 1,560	
	Operator/User	$ 120	4	$ 480	$ 120	16	$ 1,920	
Sub-total				$ 1,350			$ 3,960	
Sample Processing	Handling	$ 65	4	$ 260	$ 65	16	$ 1,040	SED-FSP sediment validation costs for sample collection at 25% of total locations.
	Processing/Prep.	$ 65	2	$ 130	$ 65	8	$ 520	
	Custody/Management	$ 120	2	$ 240	$ 120	4	$ 480	
	Shipping	$ 65	2	$ 130	$ 65	4	$ 260	
Sub-total				$ 760			$ 2,300	
Demobilization	Cleaning/Breakdown	$ 120	4	$ 480	$ 120	4	$ 480	
	Packing	$ 65	8	$ 520	$ 65	8	$ 520	
	Shipping	$ 65	4	$ 260	$ 65	4	$ 260	
Sub-total				$ 1,260			$ 1,260	
Reporting	Reporting	$ 120	16	$ 1,920	$ 120	16	$ 1,920	
Sub-total				$ 1,920			$ 1,920	
Total Labor Costs				**$11,280**			**$11,050**	
Non-Labor Costs		Rate	Units	Cost	Rate	Units	Cost	
Materials Costs	Core Liners	$ 25	8	$ 200	$ 25	32	$ 800	SED-FSP sediment processing costs for sample collection at 25% of total locations.
	Sample Containers	$ 5	8	$ 40	$ 5	32	$ 160	
	Cleaning Supplies	$ 25	1	$ 25	$ 25	4	$ 100	
	Shipping Supplies	$ 25	1	$ 25	$ 25	4	$ 100	
	Other Misc.	$ 25	1	$ 25	$ 25	4	$ 100	
Sub-total				$ 315			$ 1,260	
Analytical	ASTM D422	$ 100	8	$ 800	$ 100	32	$ 3,200	Documented costs.
	Laser Diffraction (Malvern, Horiba, e.g.)	$ 115	8	$ 920	$ 115	32	$ 3,680	Historical Costs.
	Electrozone Sensing (Coulter Counter)	$ 150	8	$ 1,200	$ 150	32	$ 4,800	Discussion with laborartory representative.
	Microscopy	$ 200	8	$ 1,600	$ 200	32	$ 6,400	Estimation.
Project Cost	ASTM D422			$12,395			$15,510	Totals according to analytical methods for 2-day survey, 32 surface sediments collected and analyzed.
	Laser Diffraction			$12,515			$15,990	
	Electrozone Sensing			$12,795			$17,110	
	Microscopy			$13,195			$18,710	

Table 8. Cost comparison of a survey for grain size using the SED-FSP system and traditional sediment sample collection and analysis by standard method, excluding site-specific calibration costs.

Project Cost	ASTM D422		$ 9,170		$15,510	Totals according to analytical methods for 2-day survey, 32 surface sediments collected and analyzed.
	Laser Diffraction		$ 9,170		$15,990	
	Electrozone Sensing		$ 9,170		$17,110	
	Microscopy		$ 9,170		$18,710	

8. IMPLEMENTATION ISSUES

8.1 COST OBSERVATIONS

The capital costs for the technology would be expected to be recovered quickly as they are low. The key cost drivers are labor, deployment costs, transportation/shipping, and capital equipment costs. The costs are the standard costs that are normally associated with sediment sampling field deployments.

8.2 PERFORMANCE OBSERVATIONS

The field unit performed in accordance with laboratory observations of the developmental unit. Deviations from performance objectives occurred when sampling near shore at NASNI IR Site 9 into unsaturated sediment and on the sand cap where strong vertical gradients made it difficult to match SED-FSP profiles with samples near the sand/native sediment interface. The SED-FSP could identify the interface at the sand/native sediment types, but care should be employed where these types of situations may occur.

8.3 SCALE-UP

The demonstrations were performed at full scale. Scale up of this technology will not be a factor. The demonstrations at NBSD Chollas Creek and NASNI IR Site 9 are known to the investigators as representative of sites where the technology benefits can be employed. The thin-layer cap on the Anacostia River was installed as a study site, and as such, is small compared to actual applications of contaminated sediment caps. Nevertheless, sufficient grain size profiles were taken from the Anacostia site to demonstrate the technology.

8.4 LESSONS LEARNED

Several important lessons were learned during the progression of the demonstrations. Subsurface obstructions impose severe risks of breakage of the probe. This occurred at the IR Site 9 location and caused the survey to be delayed a week. Use of a video monitoring system is critical and should not be overlooked. In addition, the need for calibration of the unit with site-specific sediments was not expected. Application of the global calibration parameters (Section 5.2.4) will be monitored as the technology matures. Of potential interest is the development of an alternate method of pre-deployment calibration, whether through use of the “known” sediments or by application of an alternate noise source at the probe tip.

8.5 END-USER ISSUES

The technology was deployed at the IR Site 9 location and the data will provide ancillary support to the broad feasibility study that will occur there. The technology has also been selected to be deployed at Marine Corps Base Quantico where a thin-layer cap is scheduled to be installed. The SED-FSP will be used to verify placement of the cap.

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14. ABSTRACT

The Navy, Department of Defense (DoD), and other government and private entities are in the process of identifying, assessing, and remediating numerous hazardous waste sites that are the result of decades of waste management practices that led to the release of contaminants to soil, sediment, and groundwater in coastal environments. Knowledge of grain size at sediment study sites can provide lines of evidence that can be applied to identify potential areas of contaminated sediment and contaminant discharge zones. Field surveys for grain size can require a full sampling regime including substantial analytical costs. The sediment friction-sound probe (SED-FSP) technology was proposed to quickly acquire grain-size information at a lower cost. The overall objective of this project was to field-demonstrate the effectiveness of the SED-FSP for direct in-situ measurement of grain size at contaminated sediment and groundwater–surface water interaction (GSI) sites. The SED-FSP technology was demonstrated at three locations: (1) Naval Base San Diego at the mouth of Chollas Creek in San Diego Bay, NASNI Installation Restoration (IR) Site 9 and the Active Capping Pilot Study Site on the Anacostia River in Washington, D.C. The costs associated with implementing the technology are similar to costs associated with sediment sampling deployments. Field-testing of the unit confirmed applicability of the technology where fine sediments were differentiated from sandy sediment and between sub-classifications of sands, sediments in the clay range (< 3.9 µm) were not acquired either as a SED-FSP response or as results of laboratory analysis of site samples. Laboratory testing also showed that the SED-FSP did not resolve or accurately predict sizes of this range and smaller. The unit should therefore be considered for use where differentiation of sands and fines are required. Differentiation of silt (3.9 to 63 µm) and clay sizes was not validated.

15. SUBJECT TERMS

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